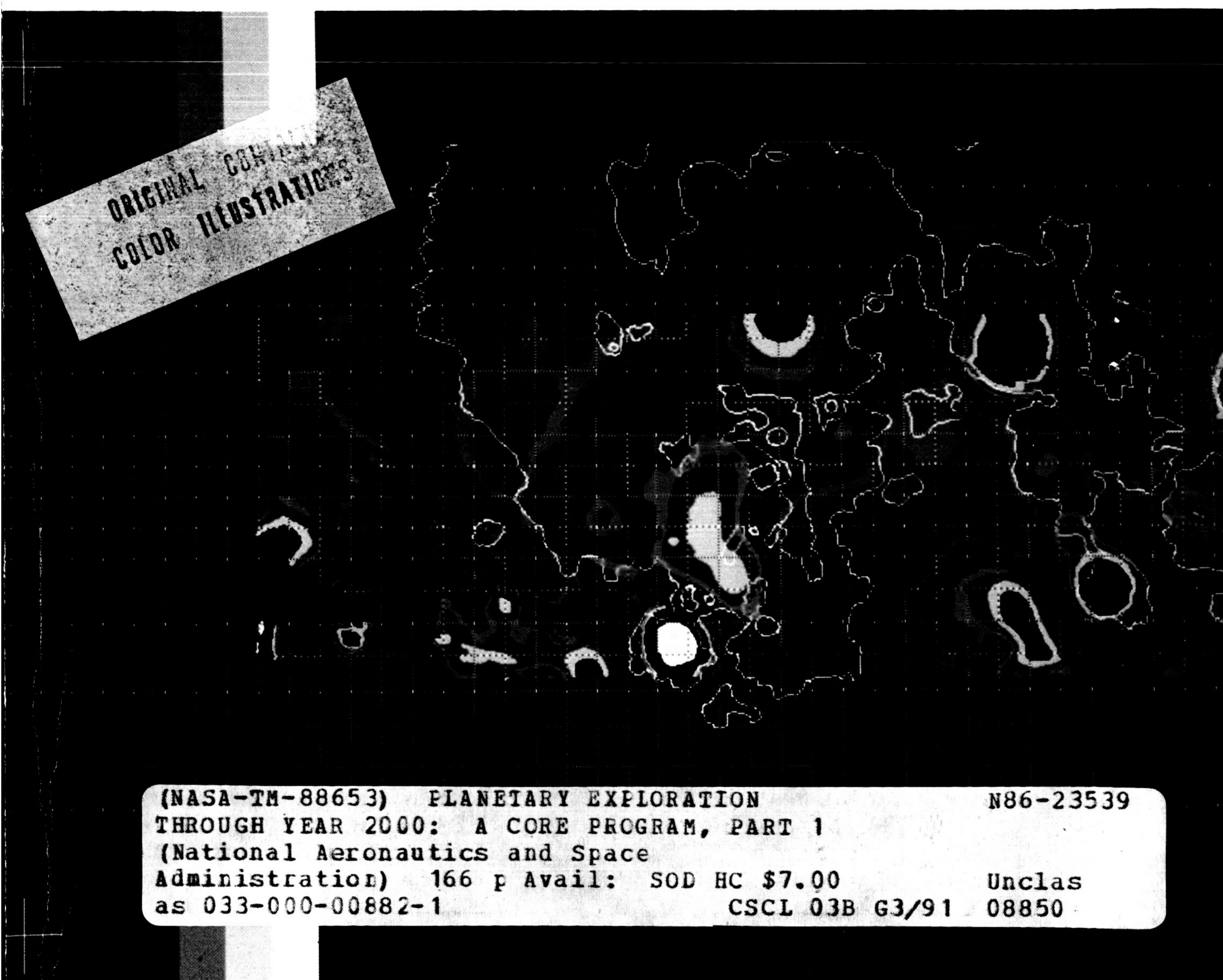
PLANETARY EXPLORATION THROUGH YEAR 2000

A CORE PROGRAM

PART ONE OF A REPORT BY THE SOLAR SYSTEM EXPLORATION COMMITTEE OF THE NASA ADVISORY COUNCIL



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Cover: ***Variations in the Moon's gravity were measured by the*** **Apollo 15** ***subsatellite then converted into this detailed map of the lunar frontside. Red represents areas of greatest mass concentration ("mascons") where the gravity field is higher than the lunar average; these areas generally coincide with the circular-shaped, maria regions. Darker colors represent areas of less gravity.***

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A CORE PROGRAM

PART ONE OF A REPORT BY THE SOLAR SYSTEM EXPLORATION COMMITTEE OF THE NASA ADVISORY COUNCIL

WASHINGTON, D.C., 1983

The Jovian moon, Europa, remains one of the solar system's most intriguing mysteries. Its cracked surface may cover a vast ocean.

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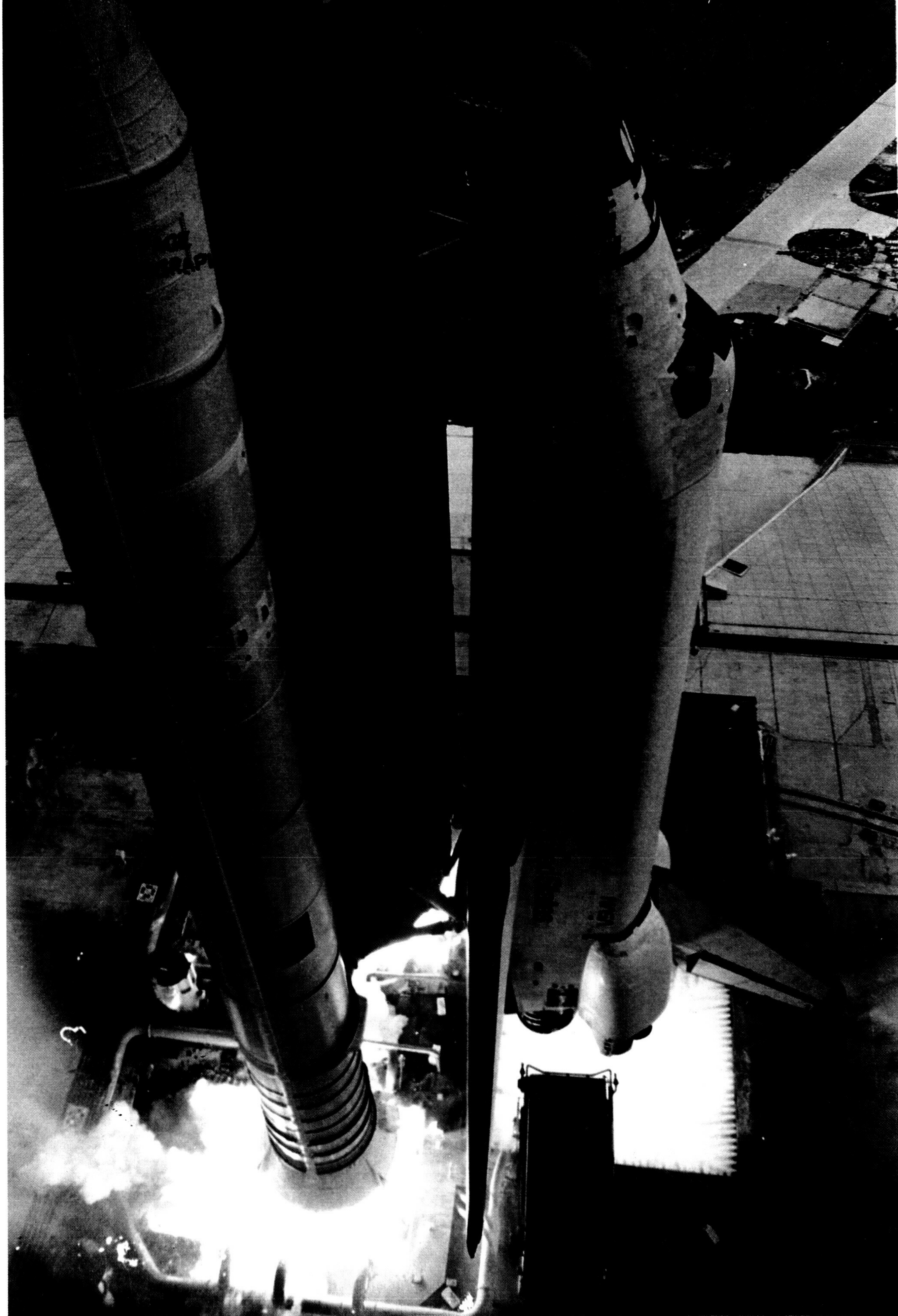

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Space Shuttle **Columbia*****, moments after its solid rocket boosters ignited, lifts off on its third orbital flight test.***

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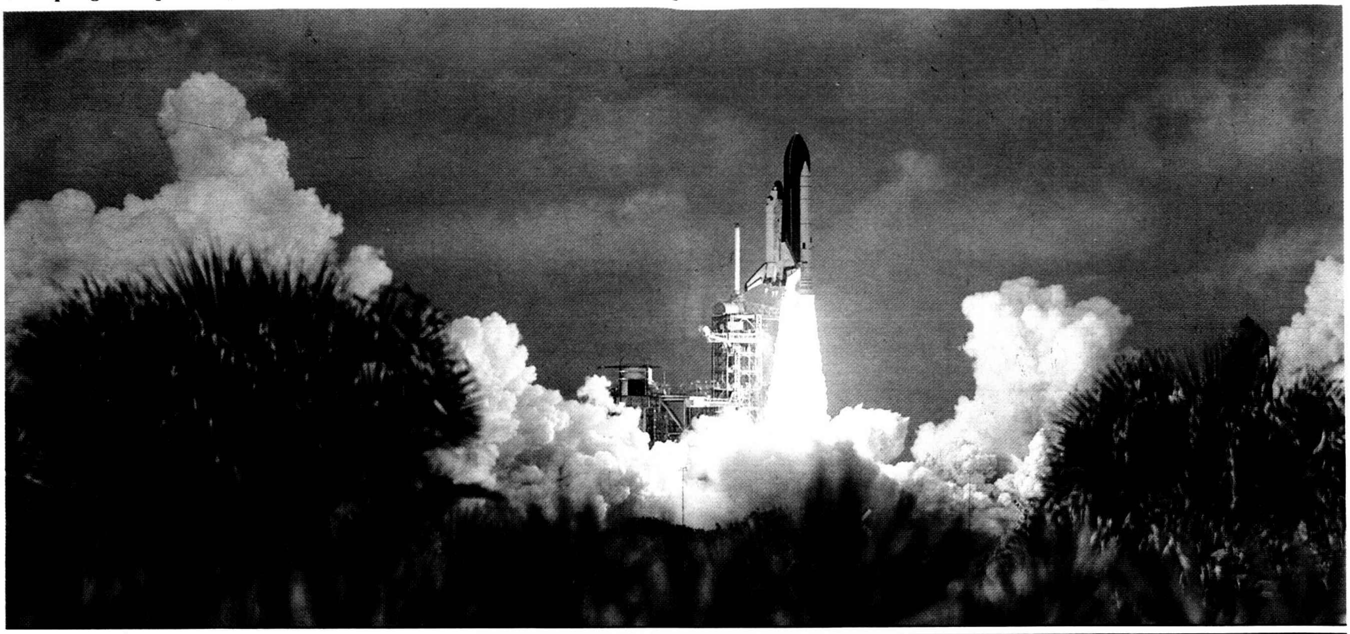
Core program spacecraft will be carried into Earth orbit aboard the Space Shuttle, *then launched toward their targets.*



1. Introduction

The exploration of the solar system by spacecraft has now spanned more than two decades and produced an avalanche of exciting discoveries and a wealth of data. More than two dozen unmanned spacecraft have transformed our view of the planets from one of shimmering, telescopic images to one of crisp, global perspectives. These new worlds amaze us with their beauty and awesome landscapes, which are the products of powerful, complex forces.

During the 20 years from the first *Mariner* flyby of Venus to the second *Voyager* encounter with Saturn, robot craft visited every planet known to ancient peoples, from Mercury to Saturn. Most of these spacecraft were launched by the United States, bearing such names as *Ranger, Surveyor, Pioneer, Mariner, Viking,* and *Voyager.* The Soviet Union, the other nation to contribute to this era of discovery, focused its efforts more narrowly on the Moon, Mars and Venus, and it too achieved remarkable successes. Thus, in less than a single generation, spacecraft have provided a close survey of 40 planets and satellites and of two ring systems.

Manned exploration has also entered the picture—dramatically—in the case of the Moon. Laboratory analyses of returned lunar samples have provided us with our most detailed understanding of planetary processes in the first billion years of solar system history, including an accurate absolute chronology. Lunar science information thus serves as a basis for the interpretation of results obtained by robotic spacecraft as they move ever deeper into the solar system.

Also during the past two decades, Earth-based telescopes have been directed toward the study of solar system bodies as yet unvisited by spacecraft—the outermost planets, the comets, and the asteroids—and have made numerous discoveries that will guide the design of

subsequent spacecraft missions. A complementary role has also been played by laboratory research on meteorites and cosmic dust, the debris from unknown asteroids and comets. These studies have provided detailed information on conditions during the earliest phases of solar system history. This information will better fall in place once we have completed a spacecraft reconnaissance of the comets and asteroids and developed an understanding of how these bodies are related to the samples in our laboratories.

Our exploration of the planets represents a triumph of imagination and will for the human race. The events of the last twenty years are perhaps too recent for us to adequately appreciate their proper historical significance. We can, however, appraise the scientific significance of these voyages of exploration: They have been nothing less than revolutionary both in providing a new picture of the nature of the solar system, its likely origin and evolution, and in giving us a new perspective on our own planet Earth.

Our approach to the exploration of the planets has been the reverse of that used over the centuries in the exploration of the Earth. From space we ***begin*** with a global view and only later move to detailed observations and measurements in selected regions. This has been a powerful approach, one that accounts for the rapid progress made to date, and one made possible only because scientists have been able to extrapolate from their knowledge of basic geological processes learned on Earth. However, the immediate global perspective tends to create an overly optimistic impression of the real state of our present knowledge. Experience has already shown that many interpretations and theoretical models based on data from first generation reconnaissance missions require radical revision in the light of data returned from later, *in situ* atmospheric and surface measurements and from the continuing analysis of returned samples (in the case of the Moon). Therefore, we know that in addition to the primary discoveries that are certain to be made by mapping the surface of Venus and by our initial encounters with the outermost planets, the comets, and the asteroids, there inevitably will be many surprises in store as we return to planets that we have visited before. Solar system exploration will certainly remain in the exciting discovery phase for at least the remainder of this century.

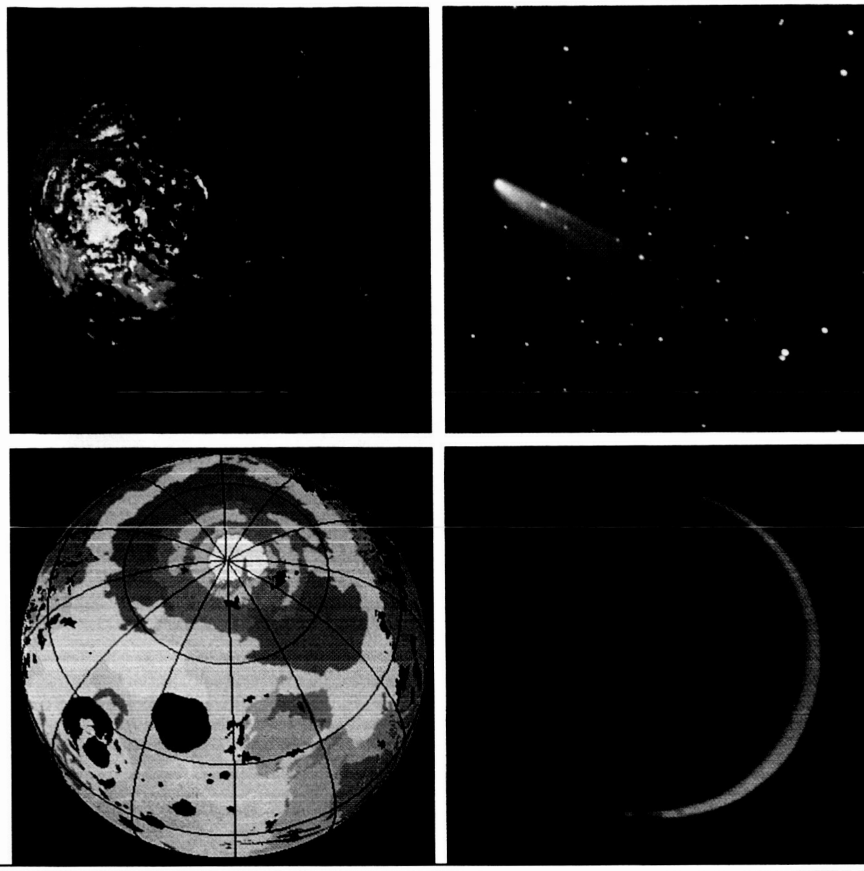
The planning that led to the earliest planetary missions of the 1960's was inevitably of an *ad hoc* nature, being influenced much more by the available performance of launch vehicles and of tracking systems than by scientific strategy. The planetary missions of the 1970's were, in contrast, designed as a program of missions by the 1968-70 Lunar and Planetary Missions Board: these were the missions that have brought us forward so spectacularly in recent years, including *Viking, Pioneer Venus* and *Voyager*. The Space Science Board of the National Academy of Sciences has put the planning of planetary exploration onto an even more systematic basis through the development of a coordinated set of scientific strategies by the Board's Committee on Planetary and Lunar Exploration (COMPLEX). These strategies were intended to guide NASA's planetary program throughout the 1980's; the *Galileo* project, now in its fabrication and test phase, was initiated in 1978 in response to the Academy's recommendations. In order to respond to the

Academy's recommendations in a fashion that would realistically reflect the changing fiscal conditions of the 1970's, the Solar System Exploration Committee (SSEC) was formed in 1980 by the NASA Advisory Council to formulate a long range program of planetary missions.

The Committee has undertaken a review of the U.S. planetary program to ensure that the nation can preserve its leading role in solar system exploration and capitalize on its 20-year investment in this enterprise. In its deliberations the SSEC was sensitive to the belief at several levels in the Agency, the Administration, and the Congress that a fresh approach to planning was in order—one that would result in a scientifically valid, affordable program of planetary exploration. Accordingly, the Committee believes that it will be necessary to set strict priorities for prospective missions consistent with the scientific strategies of COMPLEX, and to adopt lower cost, innovative approaches to their implementation. In doing so, the several, inter-related elements of the program—research, operations, and missions—must be integrated into a coherent whole. In addition NASA, the Administration, and Congress must adopt a fresh philosophy with respect to committing resources for planetary exploration. An emphasis on overall program cost should replace the arbitrary rationing of the rate of new mission activity: the control of mission costs depends upon increasing mission frequency well above the present depressed level so that the economies of heritage in hardware and software can be realized. As an immediate step forward and as part of a Core program, the Solar System Exploration Committee recommends the establishment of a *Planetary Observer* program having a modest but assured level of funding similar to the *Physics and Astronomy Explorers*. The Committee further recommends other measures, including a number of straightforward, conservative mission implementation approaches designed to reduce costs, and a restructuring of the traditional mode of mission operations. The report also provides specific recommendations on future mission priorities and on requirements for the augmentation of key supporting research activities.

Some of the highest priority scientific objectives recommended by the National Academy of Sciences are excluded from the Core program. As soon as it is feasible to do so, the Core program should be augmented by missions of greater technological challenge to allow these objectives to be achieved. Other considerations dictate the need to augment the Core program at the earliest opportunity. The Committee considers that the nation's pre-eminence in planetary exploration has made a unique contribution to, and should continue to sustain, U.S. leadership in a rapidly changing world. Planetary exploration accomplishes frontier science, provides a stimulating technology challenge, is an unmatched source of national pride and prestige, and eventually will provide the basis for economic developments in space. Investment in such exploration can, therefore, play a part in the solution to our current national economic ills.

The Committee will continue its deliberations for another year to provide both general and specific recommendations about the nature of such an augmented planetary exploration program.



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The four, initial Core missions as represented by: 1) a gobal map of Venus created from **Pioneer** ***altimeter data; 2) Comet Kohoutek in 1974; 3) a color-coded geologic map of Mars; and 4) a night side view of Saturn's intriguing moon, Titan.***

2. Recommended Program Strategy

The Solar System Exploration Committee was charged with developing a mission strategy for solar system exploration through the end of this century. The scientific priorities for this program have earlier been established by the Space Science Board of the National Academy of Sciences; these priorities have been reviewed and, where appropriate, expanded. Based on those priorities and an assessment of available technological capability and fiscal constraints, and using the expertise of the planetary science community through its four Working Groups, the Committee reaches the following conclusion with respect to the U.S. planetary exploration program:

In order to maintain U.S. leadership in solar system exploration and to realize any reasonable progress toward the scientific goals recommended by the Space Science Board, NASA should immediately initiate the Core planetary program outlined below. The Committee also urges that this Core program be augmented at the earliest opportunity with additional, more technologically challenging missions of high scientific priority and exploration content. The strategy for the Core program is described in detail below. The augmentations are the subject of a study now in progress.

The Core Program

In the view of the Committee, the highest priority for the planetary program is to implement a Core program with the vigor and continuity necessary to make major steps toward answering important basic questions about the solar system. The Core program recommended by the SSEC will support a sufficient level of scientific investigation and accomplishment so that the United States can make significant progress towards the achievement of priority scientific objectives and thus retain a leading position in solar system exploration. ***The Core program should consist of two elements: the ongoing base activities,*** including basic research, mission operations, technology development, and advanced planning; ***and the Core planetary missions program.*** If the necessary continuity of the program and budget is achieved, the Committee concludes that innovative approaches to spacecraft mission design, as discussed in this report, can sustain the Core program at a total budget level of about $300 million/year. At this level of funding, planetary missions could be carried out with a frequency that allows good use of spacecraft inheritance and commonality of systems and personnel. With the present low rate of mission activity, such economies and efficiencies are not possible.

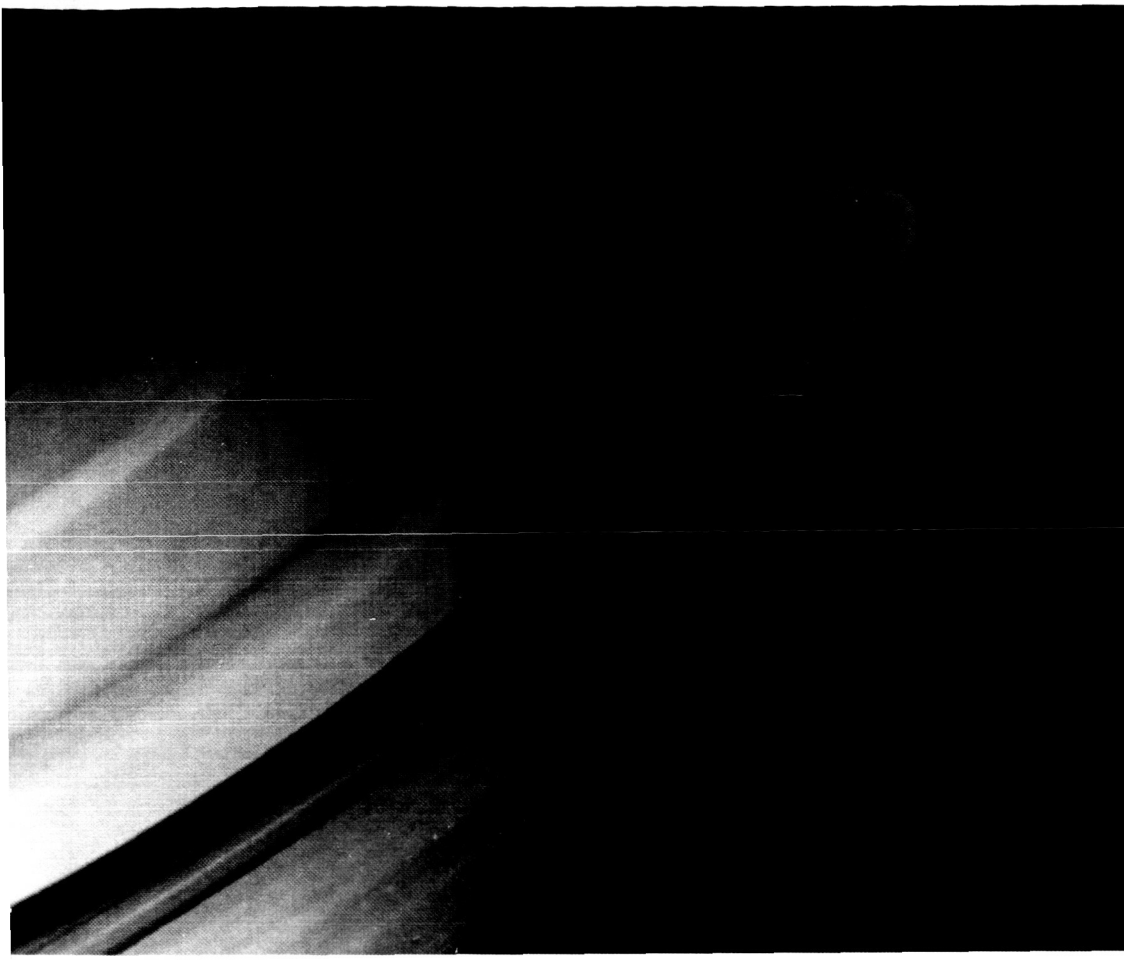
The SSEC considers that the Core program will support a sufficient level of scientific investigation and accomplishment so that the United States can retain a leading position in solar system exploration.

Missions of the Core Program

In accord with its conclusion that a balanced program of solar system exploration remains our fundamental approach, the Committee reasserts the importance of near-term missions in each of the areas of the terrestrial planets, the small bodies (comets and asteroids), and the outer planets. Based on its current assessment of technological readiness, launch opportunities, rapidity of data return, balance of disciplines, and various other programmatic factors, the Committee has identified both a specific initial sequence and subsequent Core missions in each of the areas. As discussed below, this Core program of initial and subsequent missions incorporates a variety of new methods of implementation recommended by the Committee and demonstrates that a viable level of scientific activity addressing high priority science can be achieved within a tightly constrained budget. The initial Core missions recommended by the Committee are:

1) ***Venus Radar Mapper***
2) ***Mars Geoscience/Climatology Orbiter***
3) ***Comet Rendezvous/Asteroid Flyby***
4) ***Titan Probe/Radar Mapper***

The first mission—the Venus Radar Mapper (VRM)—is required to complete the first-order characterization of the surfaces of the triad of most Earth-like planets, Mars, Earth, and Venus. Considerations of scientific importance and readiness dictate the ***highest priority for VRM,*** in which restrained scope and maximum use of spare hardware has

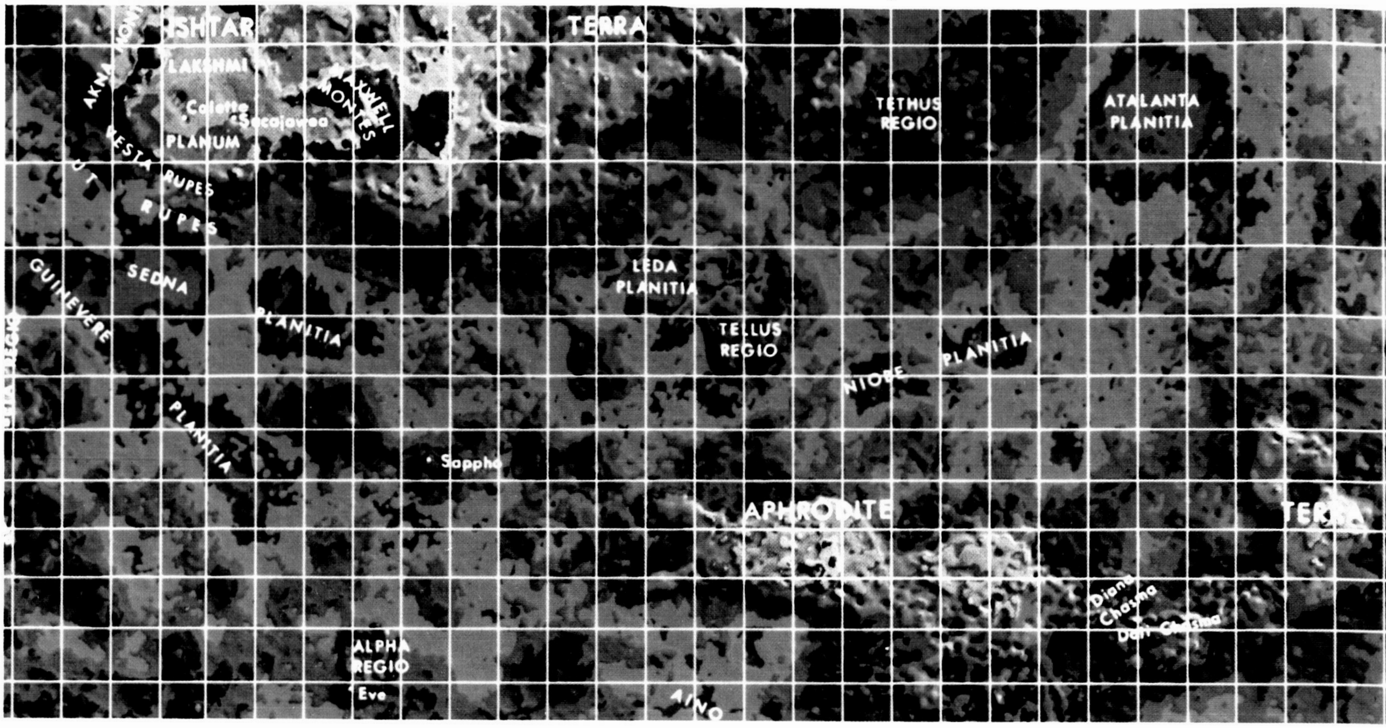


The two* Voyager *encounters with Saturn completed the initial photographic exploration of all the planets known to the ancients.

resulted in reduced mission costs. ***The* Mars Geoscience/Climatology Orbiter *is the first of a new class of* Planetary Observers *recommended by the Committee.*** The **Planetary Observers** constitute a program of ***low-cost, modestly scaled, inner solar system missions*** using already developed, high capability Earth orbital spacecraft. The **Planetary Observers** should be a ***level-of-effort program*** similar to that of the successful *Physics and Astronomy Explorers*. ***The third initial Core mission,* Comet Rendezvous and Asteroid Flyby, *requires the development of the* Mariner Mark II spacecraft,** a simple modular spacecraft that the Committee recommends be designed to accomplish, at moderate cost, missions beyond the inner solar system. Finally, the **Titan Probe/ Radar Mapper *uses* Galileo *design inheritance.***

Each of these initial Core missions is described below, as are the subsequent Core missions, all of which are directed at investigations of the terrestrial planets, the small bodies, and the outer planets. These missions are based on the detailed recommendations of the Working Groups active in each area. The ordering of missions beyond the initial ones should depend on programmatic considerations not foreseeable at this date; in setting priorities, maintenance of balance between the three areas should be an important factor.

Venus' complex topography of highlands, lowlands, and rolling plains was mapped in 1980 by the **Pioneer Orbiter.**



The Initial Core Missions

1. *Venus Radar Mapper*

Venus Radar Mapper is the highest priority mission because of its scientific and exploration content, immediate technological readiness, moderate cost, and ability to return data within months after launch. This mission will correct the current imbalance in our understanding of the Venus/Earth/Mars triad by providing basic data on the geological history of Venus. The Committee strongly recommends that it be carried out on its current schedule, leading to a launch in 1988.

2. *Mars Geoscience/Climatology Orbiter*

A remote sensing mission to Mars has high scientific priority for resolving many first-order questions related to the evolution of the Venus/Earth/Mars triad. The cost of such a mission can be reduced substantially by taking advantage of the capabilities of Earth-orbital spacecraft developed by the aerospace industry for commercial and scientific uses. Specifically, the Committee recommends the highest priority in this area for the *Mars Geoscience/Climatology Orbiter*, which should be undertaken in the near term. Two fundamental objectives of Mars exploration are combined in this mission: determination of the global surface composition and determination of the role of water in the climate of Mars. This mission will give a strong start to the *Planetary Observer* program and set the stage for subsequent missions in this class to the inner planets and small bodies.

3. *Comet Rendezvous/Asteroid Flyby*

Among the highest scientific and exploration priorities are deep-space missions to the comets and Mainbelt asteroids. These unexplored classes of physically and chemically primitive objects promise to provide profound insights into the formation and earliest history of the solar system. The coming availability of the *Shuttle*-launched *Centaur* upper stage, together with advances in spacecraft and instrumentation, now bring within our capability exciting missions to these messengers from the distant past.

A rendezvous mission with a short-period comet will produce a significant scientific return that cannot be achieved by fast flybys such as those planned by those other nations to study Comet Halley. Only an extended rendezvous mission permits the detailed analysis of a cometary nucleus required for an understanding of its origin and evolution. En route to the comet, the same spacecraft can provide a flyby encounter with a selected Mainbelt asteroid.

This rendezvous/flyby mission will be the first of the *Mariner Mark II* missions. The objectives of this mission are to: (1) determine the chemical and isotopic composition of the volatile and non-volatile fractions of the nucleus; (2) characterize the physical state of the nucleus, coma, and tail as a function of time and orbital position; (3) determine the size, shape, mass and spin vector of the nucleus; (4) map the surface morphology, albedo, thermal properties, etc., of the nucleus; (5) characterize the hydrodynamics of gas and dust outflow; and (6) determine the chemical kinetics of parent and daughter molecules in the coma.

The most desirable short-period comets are the brightest and most active. Among several opportunities in the 1990's is Comet HMP, which would yield the earliest practical rendezvous (1995). The choice of rendezvous target should be defined after further analysis of scientific and programmatic factors.

4. *Titan Probe/Radar Mapper*

The atmosphere of Saturn's largest moon, Titan, may yield insight into the chemistry of the pre-biotic state of the Earth's atmosphere. Its cold, dense, nitrogen atmosphere contains a substantial amount of methane that may well occur as methane rain, rivers and seas, a variety of photochemically produced organic molecules and a ubiquitous aerosol presumably composed of more complex compounds. The principal objectives of a Titan mission are the characterization of Titan's atmospheric chemistry and structure and the nature of its surface. To this end, the primary element of the mission is an atmospheric probe carrying, for example, ion and neutral mass spectrometers, an electron temperature probe and retarding potential analyzer, a gas chromatograph, a radiometry experiment, pressure and temperature sensors, and a descent imager. In addition to characterization of the atmosphere, critical questions about the nature of Titan's surface, whether liquid or solid, and its global variability, can be addressed by simple radar experiments carried on an accompanying spacecraft. The degree of sophistication possible for the science on the probe-carrying,

companion spacecraft is uncertain at this time. At one extreme, a simple flyby probe bus could support a minimal radar altimeter/ scatterometer to obtain a profile across the surface. At the other, a sophisticated orbital spacecraft derived from the *Galileo* design could expand enormously the scientific content of the mission, completing a broad set of other observations throughout the Saturnian system.

Subsequent Core Missions

1. Terrestrial Planets

The recommended missions for the terrestrial planets after the *Mars Geoscience/Climatology Orbiter* include the following, listed in arbitrary order:

- ***Mars Aeronomy Orbiter***
- ***Venus Atmospheric Probe***
- ***Lunar Geoscience Orbiter***
- ***Mars Surface Probe***

The *Mars Aeronomy Orbiter* is designed to explore interactions of the planet's upper atmosphere and ionosphere with radiation and particles from the Sun, and to settle the question of an intrinsic magnetic field for Mars. The *Venus Atmospheric Probe* will provide definitive information on the abundance of major and trace components of the Venus atmosphere. The abundance and isotopic composition of the noble gases are especially important for understanding the origin of the Venus atmosphere. The *Lunar Geoscience Orbiter* will provide a global map of surface composition and other properties, and decide the question of the presence of condensed water and other volatiles in polar cold traps. The *Mars Surface Probe* mission will establish seismic stations, meteorological stations, and geoscience observation sites. This mission will determine the level of the planet's seismicity, analyze surface weather data for its climatic pattern, and perform geochemical and other analyses of its surface material.

These missions and the other missions of the Core program are all of high priority in pursuing the primary scientific goals of the planetary exploration program: reaching an understanding of the present state, origin, and history of the solar system—including the Earth, and including the chemical history of the solar system in relation to the appearance of life. The lunar mission (and the Earth-approaching asteroid mission described below) also support the program's secondary goal: establishment of a scientific basis for future use of near-Earth resources. Although these latter two missions have not been planned in detail, they fall in the low-cost *Planetary Observer* class. Worthwhile cost savings can be realized on these missions using instruments and spacecraft developed for the *Mars Geoscience/ Climatology Orbiter*. The other terrestrial planet missions described here also fall into the *Observer* class, where derivatives of Earth-orbital spacecraft can be used as planetary orbiters and as probe-carrying buses.

2. Small Bodies (Comets and Asteroids)

After the initial ***Comet Rendezvous,*** the following Core missions are recommended:

- ***Comet Atomized Sample Return*** (preferably in association with the rendezvous)
- ***Multiple Mainbelt Asteroid Orbiter/Flyby***
- ***Earth-Approaching Asteroid Rendezvous***

In addition to the measurements by a rendezvous craft, we also have the capability to extend greatly our understanding of the composition of cometary material by flying through the inner coma with a simple ballistic spacecraft and returning an atomized sample of cometary dust for analysis in terrestrial laboratories. The Committee recommends that the *Atomized Sample Return* be carried out in conjunction with a *Rendezvous Mission.*

The Committee also includes in its Core program a reconnaissance and exploration mission to the Mainbelt asteroids. In order to obtain a detailed characterization of at least one such body while at the same time sampling the diversity of chemical and physical types, the recommended mission includes multiple asteroid encounters, some orbiter, some flyby. The Committee recommends that one or more coordinated orbiter-with-flyby missions to the Mainbelt asteroids be undertaken by the early 1990's.

The *Earth-Approaching Asteroid Rendezvous* will characterize one chosen member of this set of bodies. Because of its anticipated commonality with the terrestrial planets missions recommended above, the implementation approach for a mission to the Earth-approaching asteroids is described under that element of the Core program.

3. Outer Planets

Beyond the *Titan Probe/Radar Mapper* mission, the outer planets missions proposed for the Core program are:

- ***Saturn Orbiter***
- ***Saturn Flyby/Probe***
- ***Uranus Flyby/Probe***

Pioneer and *Voyager* observations of Jupiter and Saturn, and their rings and satellites have revealed a diversity of natural phenomena that are highly relevant to understanding the formative and evolutionary processes of the solar system. The systematic study of the outer planets and their complex ring and satellite systems thus remains a major element of the planetary program. The *Galileo* mission will address many of these goals for Jupiter. The next area of intensive study should be the Saturn system. Characterization of the atmosphere, environment, and surface of Titan is identified as the outer planet scientific objective of highest priority. Further characterization of the current physical and chemical states of the atmospheres, magnetospheres, rings and satellite systems of the outer planets will call for several missions, each having high priority.

Galileo probe technology is well suited for deployment of spacecraft into the atmospheres of Titan, Saturn, and Uranus; accordingly, the Committee recommends that probe missions to these planets be included in the Core program. An orbital mission to Saturn is required to address the goals related to the characterization of the Saturnian satellites, ring systems and magnetosphere. The Committee notes that a Saturn orbiter and a Titan or Saturn probe mission could be carried out with considerable cost savings by use of spacecraft and certain instruments developed for the *Galileo Jupiter* mission.

Accessibility to the outermost planets, Neptune and Pluto, within trip times of less than a decade, can be achieved with the assistance of Jupiter swingbys. However, the Committee concluded that the first such swingby opportunities occur too early in the 1990's to permit a mission to Neptune to be included in the Core program.

Technology Requirements

Execution of the missions recommended by the Solar System Exploration Committee needs no enabling technology development beyond that already well underway—the *Shuttle*-compatible *Centaur* upper stage. However, the low-cost guideline of the Committee's deliberations implies the judicious selection of certain straightforward new technology developments to increase the cost effectiveness of the recommended programs.

For instance, in the area of upper stage propulsion, the 2-stage *IUS* has more capability (at relatively high cost) than necessary for a number of recommended missions, while the *PAM-A* launch vehicle is insufficient (Figure 1). Thus, it may be cost effective to develop a low-cost intermediate stage or motor to fill this "gap" in launch capability. The Committee recommends further study of this issue.

No new technology is needed to use Earth-orbital spacecraft derivatives for planetary exploration; however, some changes to these Earth-orbiting spacecraft subsystems will be necessary for planetary applications. To achieve greater cost effectiveness in *Mariner Mark II* missions, the Committee recommends the continuation of technology developments in several subsystem areas, including telecommunications, data systems, and power.

To achieve significant cost savings for all missions, the creation of an up-to-date mission operations system is required. This system must be capable of handling the operations of all of the missions of the Core program on a common basis, must take advantage of state-of-the-art computer technology, and must seek to reduce the labor-intensiveness of traditional operations. Furthermore, the archiving and distribution of data must also be brought up to date consistent with the recommendations of the Space Science Board's Committee on Data Management and Computation.

Supporting Research

The successful, effective execution of the recommended Core program requires a vigorous research base that will provide the scientific and technological foundation for the program. The scientific foundation

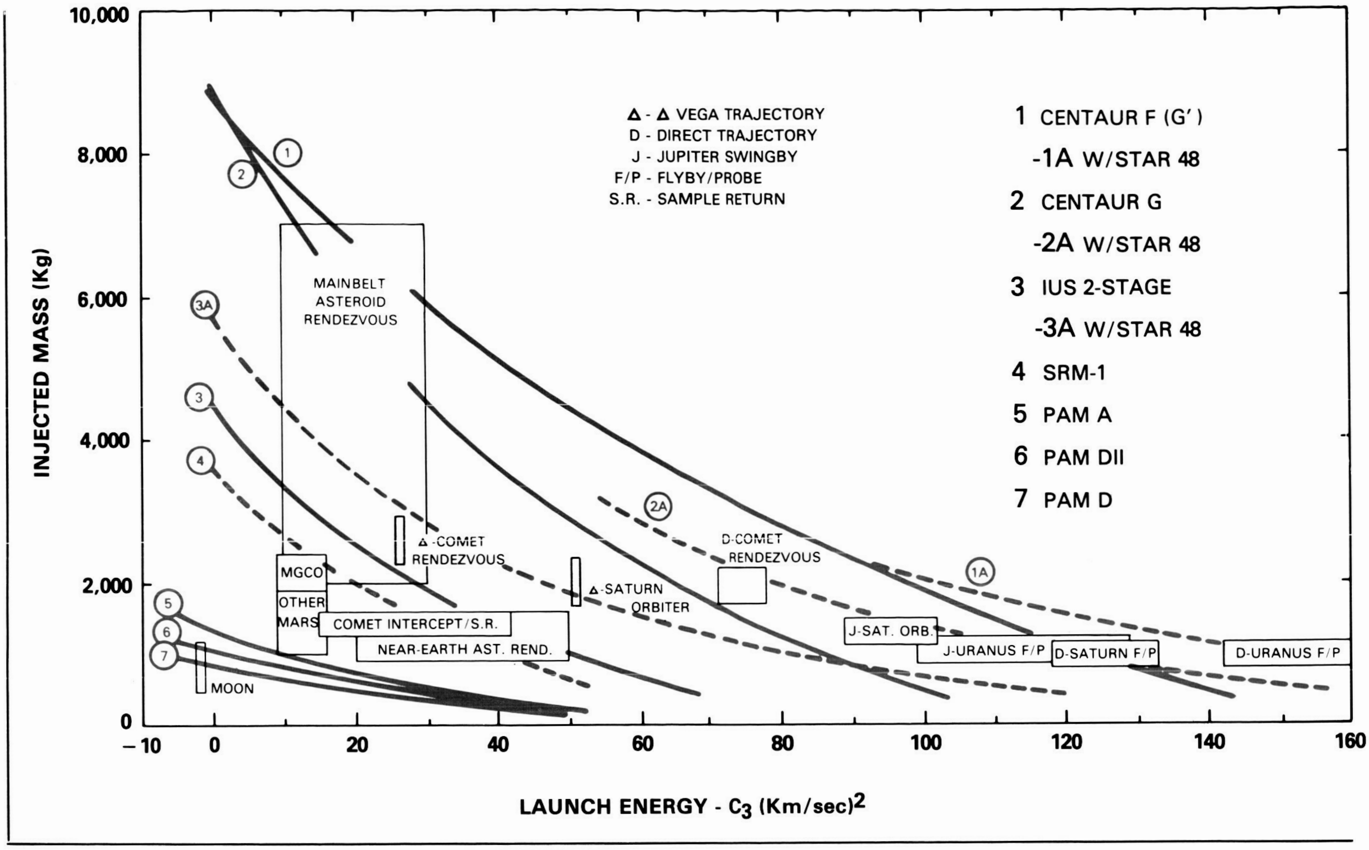


FIGURE 1. ***SHUTTLE* UPPER STAGE PERFORMANCE**

requires the in-depth analysis and synthesis of data and samples from past missions augmented by a focused program of theoretical and experimental studies, telescopic observations (both ground-based and Earth-orbited), and by the laboratory analysis of meteorites and cosmic material. Recent NASA budget requests in this area have been alarmingly low, threatening the entire foundation of the planetary program. Accordingly, ***the Committee endorses NASA's stated plan to restore the level of activity in the planetary exploration research and analysis area to at least the "minimum" level of FY 1981.*** This restoration should be made immediately. It will then still be necessary to augment the research effort, as described below, to ensure adequate support for the mission activity of the Core program.

The Planetary Program to date has a mixed record in supporting the in-depth analysis of mission data and samples—the ultimate goal of the program. In the case of the *Apollo* samples and the *Viking* data, resources were specifically allocated for this purpose with the result that many scientists, in addition to those on the flight team, participated in the data analysis activity; our understanding of the Moon and Mars thus continues to grow. The *Apollo* samples, in particular, have proven to be a virtually inexhaustible source of information, capable of being mined repeatedly as new laboratory techniques are developed and new insights are gained. The *Viking* data are more limited in scope but are so voluminous that it will be years before we have fully exploited the legacy of this mission.

For the *Voyager* and *Pioneer Venus* programs, however, the record is much less encouraging. Because of constrained funding, data analysis for these missions has been proceeding slowly and has been limited almost exclusively to flight team scientists. Since both missions have been spectacularly successful in acquiring wide-ranging multidisciplinary data sets, it is highly regrettable that no provision has been made to systematically analyze and synthesize these data. The absence of a strong *Voyager* Data Analysis Program, in fact, already has hampered the planning and selection of appropriate targets for remote measurements to be made during *Galileo's* encounters in the Jovian system. NASA's failure to expend even modest sums to analyze the *Pioneer Venus* data has left the goals of that program incompletely realized.

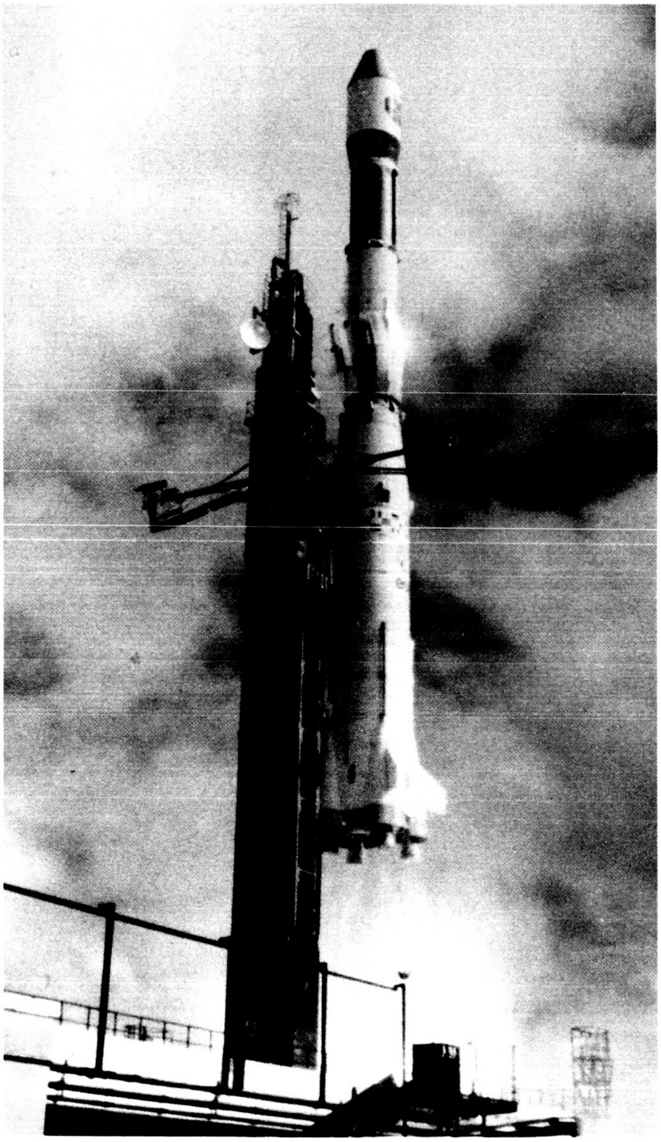
The Committee notes that resources to undertake in-depth analyses of planetary mission data generally are not identified and protected at the initiation of planetary missions but are sought only after the data have been acquired. Despite the obvious priority of such an activity, the needed resources have not been forthcoming, especially in the case of recent, ongoing missions. Therefore, the Committee urges that ***for all future missions, provision for data analysis be made at the time of inception for this final, essential mission phase.***

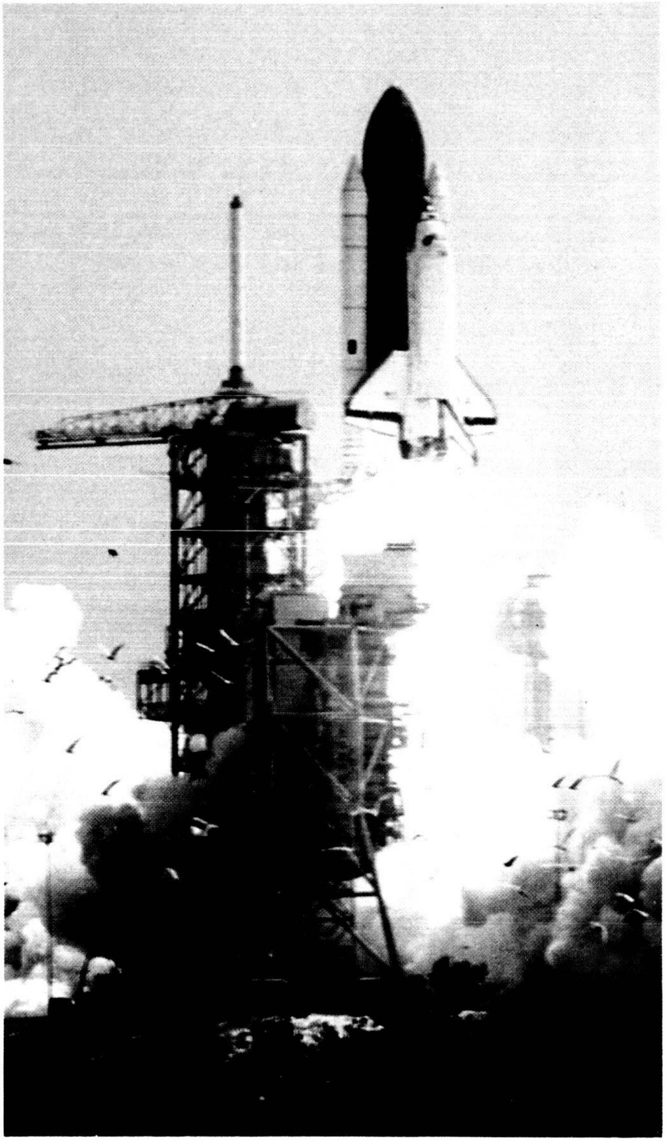
Since the current backlog of unreduced data will be compounded by the exceedingly voluminous data that will be returned by *Galileo*, the Committee also ***recommends that resources be made available immediately for the in-depth analysis of the*** **Voyager** ***and*** **Pioneer Venus** ***data sets.*** Given such resources, the planetary sciences community could take advantage of the current lull in mission activity to complete the analysis of available data prior to the return of data from the *Galileo* spacecraft and those of the recommended Core program.

The technological foundation of the program, in addition to that involved in development of new and cost-reducing technologies described above, includes the development of state-of-the-art instrumentation to ensure maximum productivity from spacecraft missions. It would be unconscionable to recommend a series of missions that rely entirely upon currently available experiment designs; the very purpose of continued planetary exploration would be compromised. Currently available flight instruments must be upgraded, new measurement concepts must be explored, and state-of-the-art instruments developed. Accordingly, ***the Committee strongly recommends that NASA provide vigorous support for instrument/experiment development.***

The Committee points out that there also is a need to provide opportunities for new investigators, particularly young investigators, to participate in the basic research programs and in the data analysis and interpretation of ongoing missions. Long-duration planetary missions periodically should be infused with new talent. Ongoing missions and research programs should provide training for young scientists, on whom the future of the planetary exploration program depends. A vigorous guest investigator program can provide an effective means for new investigators to participate in ongoing missions while an adequately supported research program will allow for the continued entry of future science leaders.

The European Space Agency's Ariane *(left) and the U.S.* Space Shuttle *(right) will launch planetary missions of the future.*





International Cooperation

In the 1960's and 1970's, planetary science was clearly dominated by the United States, with major contributions by the U.S.S.R. The trend in recent years has been an increase, relative to the U.S. and the U.S.S.R., in the capability and interest of other nations to participate in planetary science and exploration missions. This increasing interest has occurred against a backdrop of budgetary constraints in all nations, together with increasing sophistication and cost of planetary missions. Combined, these factors suggest that more planetary science can be accomplished in a given period if interested nations coordinate their planning and, occasionally, undertake joint missions.

Coordination of planning is a minimal step necessary to avoid non-productive studies and mission duplication. Mutual agreement of

elements of individual national plans can further lead to enhanced efficiency by synergistic coordination of data gathering by separate spacecraft, by shared launch and mission operations, and by cooperative data exchanges and interpretation.

A second level of cooperation involves the joint planning and implementation of a mission in which partners depend on each other. This level of cooperation necessarily demands mutual trust and the strongest possible commitment to completion of the project. In return for the increased management complexity and subjugation of individual identity, a cooperative mission ought to be one that would otherwise not be implemented in either party's individual program, generally for budgetary reasons. This is an ***enabling*** concept of cooperation.

The Committee recommends that both types of international cooperation be pursued. In so doing, it is essential that the base U.S. program remain strong. Thus, specific cooperative endeavors ought to be consistent with the SSEC implementation strategy and their merits assessed accordingly.

Resource Requirements

The recommended Core program requires the resources indicated in Figure 2. The total is the sum of three separate budgetary requirements: resources for research and analysis (R&A), for mission operations and data analysis (MO&DA), and for development flight projects. The R&A budget supports a spectrum of activity including ground based astronomy, laboratory and theoretical efforts, cartography, and meteorite analysis. It also includes resources to analyze mission data after the data are released to the community at large (such "data" include the *Apollo* lunar samples as well as *Viking, Pioneer Venus* and *Voyager* data). The R&A budget additionally includes the resources to plan future missions through the pre-project definition stage and to undertake the early development of instrumentation for future missions. The MO&DA budget pays for the operation of missions after launch (currently *Pioneers 10-11, Pioneer Venus,* and *Voyagers 1 & 2),* including science team support and including data analysis while the data are proprietary to the selected teams (one year after acquisition). The budget for development flight projects supports approved projects through launch; this item currently includes only the *Galileo* project. (For a comparison of the Core program recommended budget with past planetary exploration funding, actual and projected, see Figure 3).

In the budget projection contained in Figure 2, the Committee sought to achieve a realistic and responsible funding plan for the program: a buildup to a roughly constant level of resources whereby the recommended missions of the Core program can be launched by the year 2000. To this end the R&A budget has been constrained to grow gradually to a level able to adequately support the Core program. A drastic, but realizable, change in the mode of undertaking mission operations is required to restrain the MO&DA budget line to the level indicated ($60M per year). Specifically, the Core missions must be

FIGURE 2. **FUNDS REQUIRED FOR CORE PROGRAM**

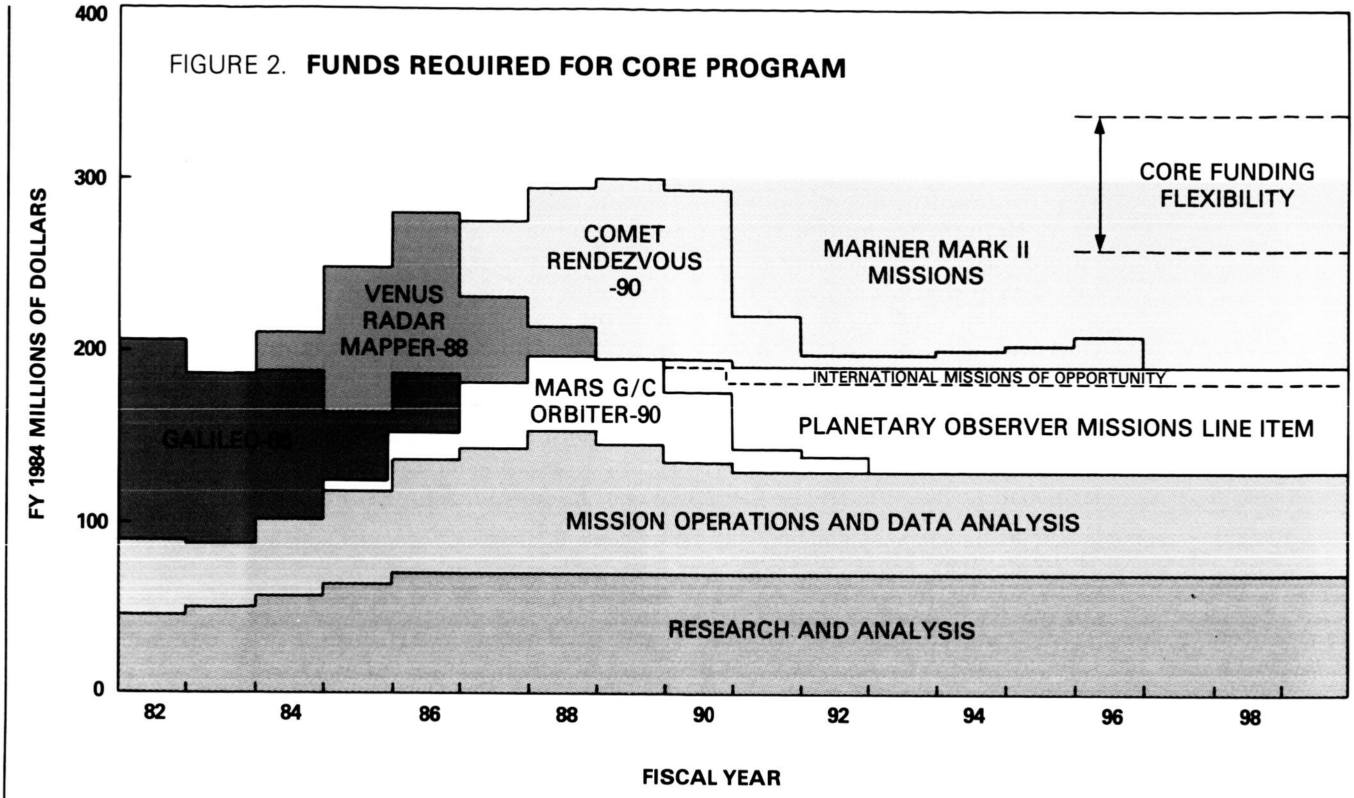
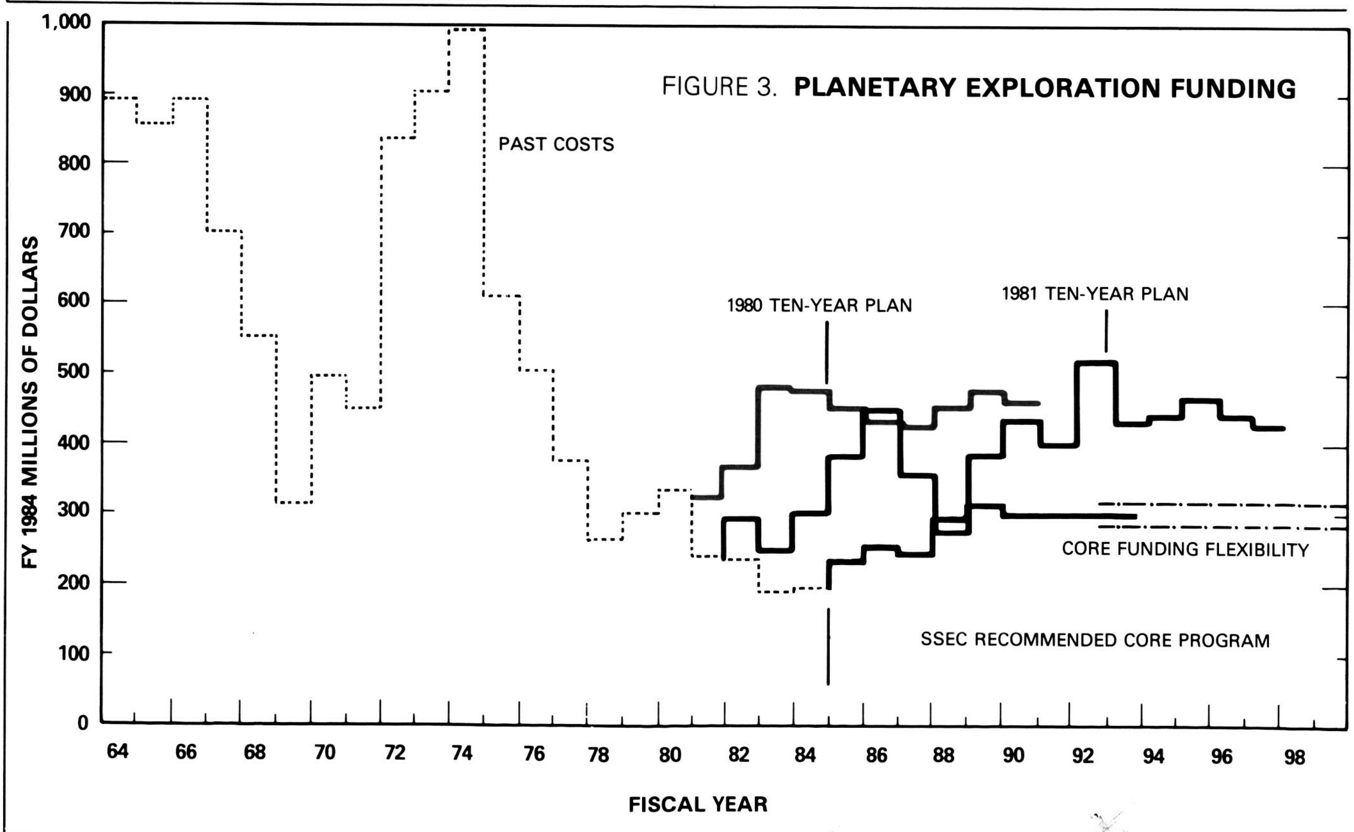


FIGURE 3. **PLANETARY EXPLORATION FUNDING**



planned for a common operations system as opposed to the custom-built operations system approach that has prevailed to date. The required multi-mission operations system calls for organizational more than technological innovation. Given the availability of a long-range mission plan—the recommended Core program—there is no obvious impediment preventing conversion to a multi-mission approach after *Galileo.* A significant effort is already directed toward that end and will receive SSEC oversight. The end result in the MO&DA area is an essentially level, and relatively modest, budgetary requirement where any mission-unique operations needs are contained in the corresponding development flight project budget.

Once the Core program activity has been established (after a transition involving the *Galileo* and *Venus Radar Mapper* missions), the development flight projects fall into two classes—*Planetary Observers* and *Mariner Mark II* missions.

The *Planetary Observers* consist of the inner solar system missions—those undertaken by modifying Earth-orbital spacecraft. The *Mariner Mark II*'s are missions to comets, Mainbelt asteroids, and the outer planets. Both the *Planetary Observers* and the *Mariner Mark II* missions lend themselves to coherent ***program*** development (as opposed to a series of unique, unrelated projects) and, particularly for the *Planetary Observers,* to modestly scaled, level-of-effort budgeting similar to that of the successful *Physics and Astronomy Explorers* (Figure 4). The *Planetary Observers,* which require about $60M per year, would be initiated by the *Mars Geochemistry/Climatology Orbiter* in FY 1985. Continuity of funding would allow the earliest follow-on of a *Lunar Geochemistry Orbiter* and Earth-approaching asteroid missions using similar science payloads. As an additional benefit, a *Planetary Observer* budget "line item" could also support the development and fabrication of U.S. instruments to fly on foreign spacecraft. (The European Space Agency has opened its experiment selection process to allow U.S. participation but, because of the necessarily long lead time, NASA's budget structure does not allow advantage to be taken of this opportunity.) The year-to-year stability of this type of funding also would permit the support of missions carried out in collaboration with other nations.

The *Mariner Mark II*'s require about $100M per year on average, taking into account the resources need to continue advanced technology development for subsequent *Mariner* missions. The first *Mariner Mark II* mission would be to rendezvous with a short period comet, requiring a project start as early as 1987. Launched using the *Shuttle/Centaur* as early as 1990, the spacecraft would reach the comet in the mid-1990's.

Together with the R&A and the MO&DA budgets, the funding required to undertake the Core program of *Planetary Observer* and *Mariner Mark II* missions is about $300M per year in FY 1984 dollars (the specific required level depends upon the degree of international collaboration). Although this amount is many times ***less*** than historical highs for the program, the anticipated yield is comparable to that of the 1970's when planetary exploration enjoyed a golden age.

The unprecedented level of productivity is achievable because the Core program missions are low in technical risk while high in scientific

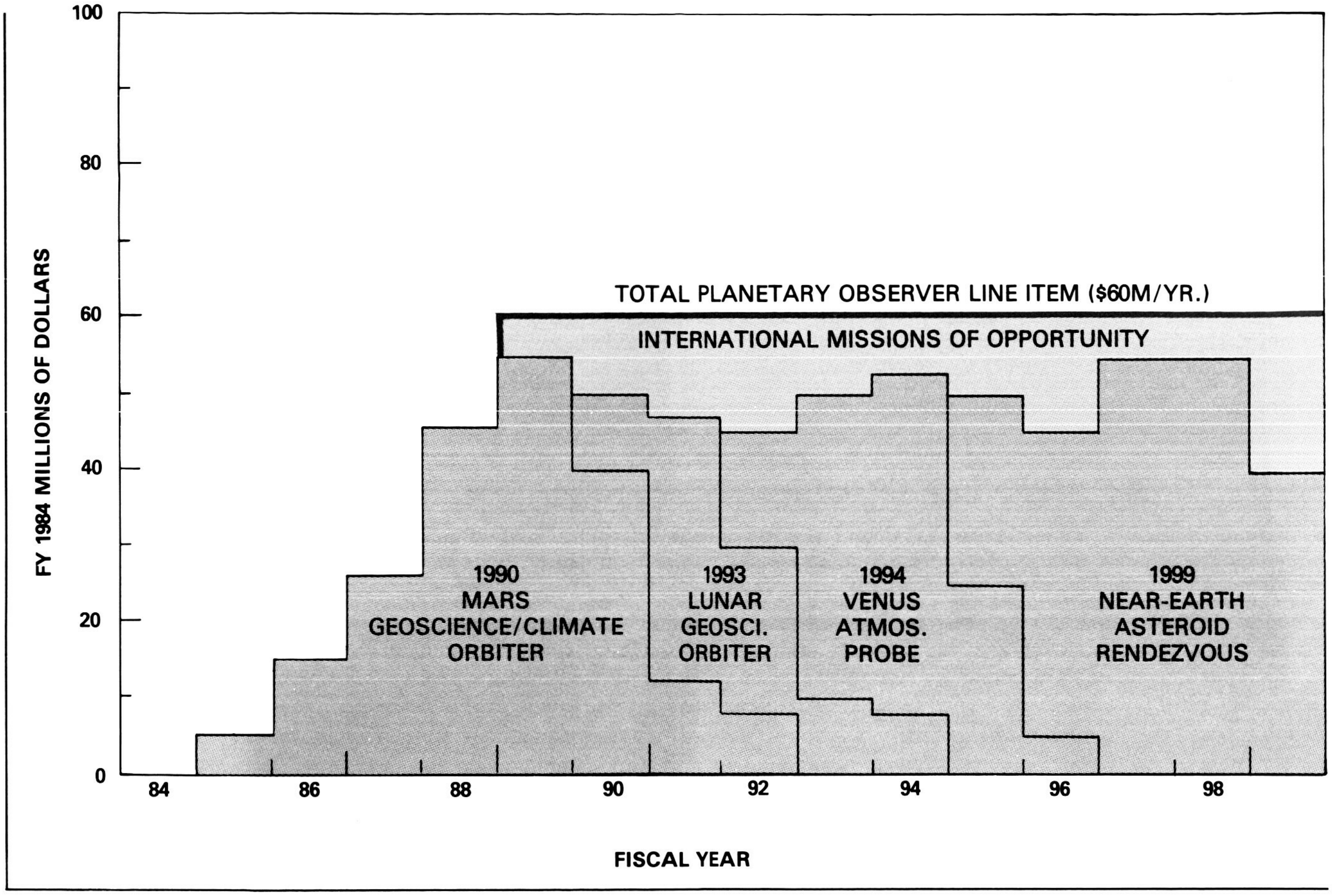
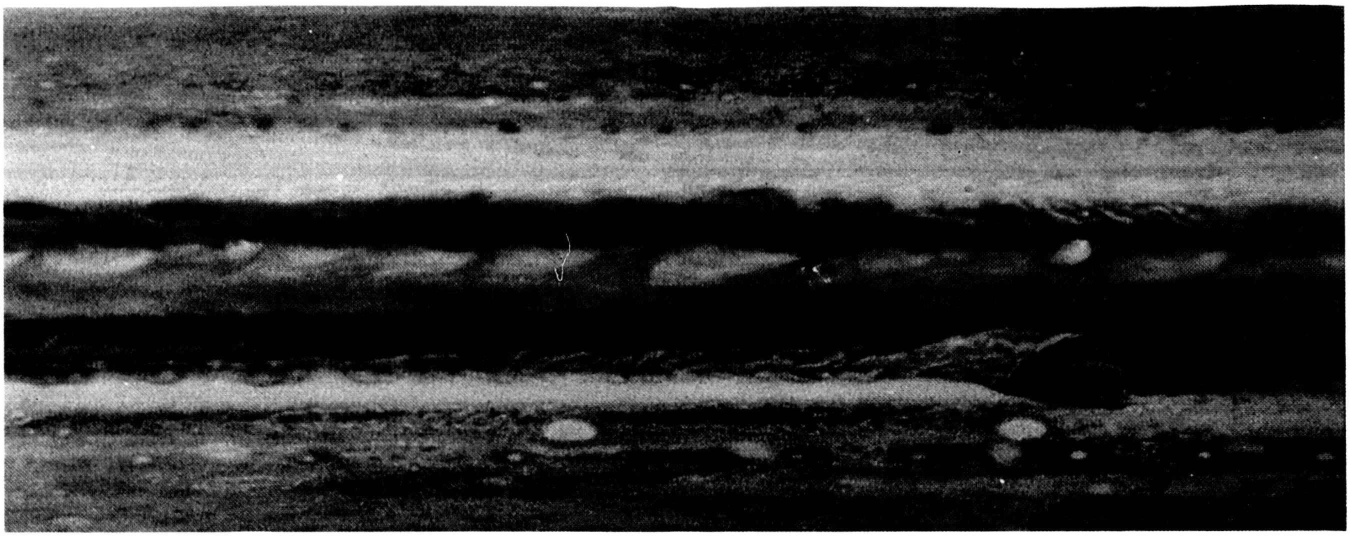


FIGURE 4. ***PLANETARY OBSERVER* CANDIDATE PROGRAM**

content; costly technological challenges are not required. Instead, NASA can take advantage of, and capitalize on, its prior investment in planetary exploration. An essential feature of the Core program is the high frequency of activity in each of the two mission implementation approaches—the *Planetary Observers* and the *Mariner Mark II* deep space missions. Together with the program's research framework and the multi-mission operations system, these two mission sets make up the four, intimately linked components which comprise the whole program.

At times of great fiscal stress, such as the present, NASA has tended to ration new starts in each of the space science disciplines to one every several years. This approach can become counterproductive, as is certainly now the case in the area of planetary exploration. ***By constraining total annual expenditures to a reasonable level rather than by placing an arbitrary ceiling on the number of new starts, NASA can renew its planetary exploration program without jeopardizing the health of any other area of the space sciences, all of which have an essential role to play in the nation's future.***

A computer, using Voyager 1 *photography, generated this map-like Mercator Projection of Jupiter.*



Augmented Program

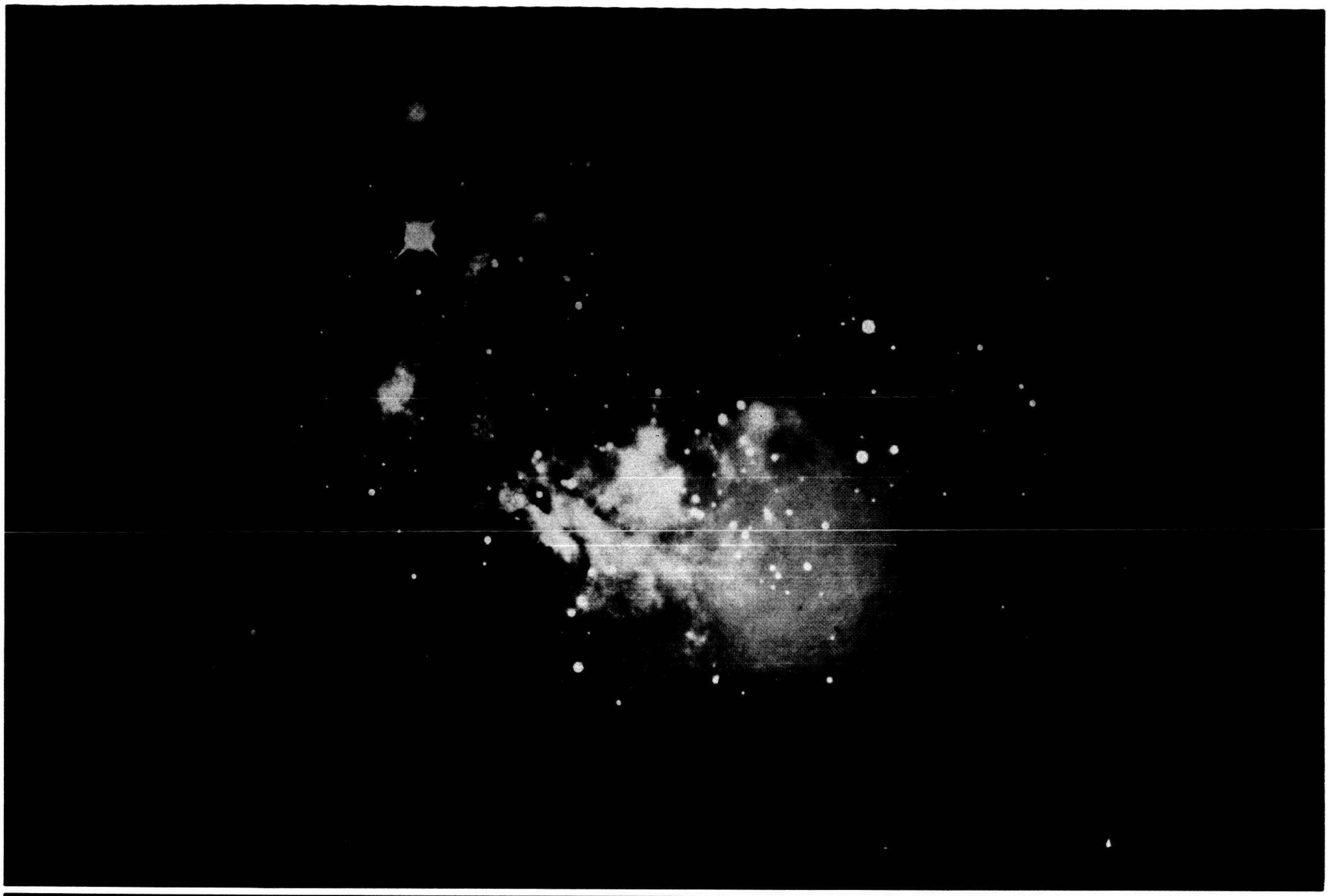
Many scientific goals of the highest importance (e.g., the return of samples from Mars, the exploration of Titan's surface, the return to Earth of pristine fragments of comets and asteroids for laboratory analysis) are excluded from the Core program on the basis of cost alone. If the past continues to be a guide, the achievement of these science objectives will require that the more ambitious missions also be capable of addressing other important national goals. During the last two decades it has been amply demonstrated that the U.S. planetary exploration program, while pursuing goals of science and exploration, is also able to successfully achieve other goals. Among these are: stimulation of high technology, enhancement of national pride and prestige, demonstration of U.S. technological capability in a peaceful context, and creation of a positive climate for the scientific education of the nation's youth. The Core planetary exploration program outlined above will continue to make a significant contribution to these ends but will fall far short of that achieved earlier. Therefore, ***the Committee recommends that the Core program be augmented at the earliest opportunity by missions of the highest scientific priority that are also significantly more technically challenging than those of the Core program.***

Although the Committee's deliberations have not yet included more ambitious missions than those in the Core program, the Committee recognizes the need to provide the Agency with recommendations on the following subjects:

- More challenging missions of the highest scientific merit to the inner planets, outer planets, and small bodies;
- Missions needed to lay the groundwork for the eventual utilization of near-Earth resources; and
- The role of a space station in the implementation of missions in the above categories.

The Committee expects to require an additional year of activity to identify appropriate approaches to these ends.

This composite, infrared view of the Orion Nebula depicts regions of "proto" stellar formation among the nebula's gasses.



3. Background

This report deals with the United States' Planetary Exploration Program, the purpose of which is to achieve a deep understanding of the solar system, the planets and the Earth. The motivations for achieving this insight are at least two-fold.

The first is to understand the solar system and its origin, one of the longest standing goals of human thought. The planetary research program's ultimate objective is to discover how the basic physical laws operate to produce the world in which we live. Such understanding allows us to attempt to predict and control those natural phenomena. Planetary science uses theory, experiment, and observation to turn knowledge of natural laws into understanding of the world. A major goal of this inquiry is an understanding of the origin and cosmic prevalence of life. The second motivation is the recognition that the solar system is the entire extended environment of mankind. There is no conceptual barrier to expanding the sphere of major human activity ultimately to fill this environmental niche.

The Historical Setting

Since at least the beginning of recorded history, people have observed the sky and wondered about the constitution of the heavenly bodies. They have marveled at the regular motions of the stars and were once perplexed by the peculiar wanderings of the planets. Many of the first tentative advances in mathematics and science were the result of early attempts to bring some regularity and understanding to these observations. Then, even as now, the scientific study of natural bodies, and the quest to push understanding to its farthest limits, generated much of the basic foundation of knowledge and technical capability that has been essential to the development of technological societies and economies. It is not an accident that our understanding of the cosmos and the technical achievements of our civilization have progressed together, each supporting and advancing the other.

Throughout history some questions have occupied a special and continuing place at the forefront of inquiry and research. People have wondered about the constitution of the stars and planets; they have wondered about the similarities, differences, and relationships among the distant bodies and our own Sun and Earth; they have wondered about the origin of Earth and the solar system in which we live; they have wondered about the sequence of events that led to our present existence on Earth; they have wondered whether these events are unique or commonplace in the universe, whether habitable planets are rare or abundant, and whether life—even intelligent life—is common or uncommon.

It is remarkable and awesome to contemplate that, after the whole history of human development, during which such questions have been among the central concerns of scientists and natural philosophers, we live in the time of transition from essential ignorance to real knowledge and understanding of these mysteries. Although this time of transition is indeed special, it did not come about suddenly or without precedent. The great advance of understanding began hundreds of years ago with the demonstration of the real configuration of the planets and their motion about the Sun. Progress was slow at first. But it was not long after this first part of an accurate world-view became available that the first great understanding of the behavior of matter—Isaac Newton's Theory of Universal Gravitation—was devised to account for it. The success of this theory provided an early reason to believe that all objects in the universe were governed by universal physical laws accessible to human understanding. With this auspicious beginning, more detailed observations and measurements were undertaken, and more perceptive, deeper theories have emerged with ever increasing rapidity.

With the passage of time, more and more of nature's basic mysteries have given way to the pressure of scientific investigation. By the 1950's our knowledge had progressed to the point that we could claim to have a confident understanding of the constitution of matter and its basic interactions, under most familar conditions. This gave us the tools we needed—tools that have been absent through all of preceding history. Except under conditions that occur in certain exotic places and times in

the universe, our basic understanding of matter and physical laws is such that there is no longer an impediment to answering many of the questions listed earlier.

At the same time that our understanding of matter and our grasp of basic physical laws became adequate to the task, we also had begun to develop critical technological tools and skills. Among the most recent of these is our ability to send instruments and even people into space to previously unknown regions, and to gather new information and new clues with which to construct the answers we seek.

We are at the beginning of a great advance in human understanding, if we have insight and the resolve to make use of the tools we have developed. Certainly our ignorance still far exceeds our knowledge. Yet even at this point we have a set of working ideas that give us an outline of the answers and allow us to see the shape of future investigations.

Major Scientific Goals

The scientific agenda of the United States' planetary program is shaped by a number of specific goals and expectations:

We expect to gather information crucial to our understanding of the conditions and physical phenomena that produced the solar system. This information is contained in the physical and chemical structure and composition of the solar system bodies—the Sun and planets, satellites, asteroids and comets, as well as meteoroidal debris. The formation of the solar system is a particular example of the more general process of star formation which continues today throughout this galaxy and others. Detailed studies of particular planets complement the broad range of astrophysical investigations of star formation. From astronomy we learn about the general conditions and environments in which star formation takes place. From planetary studies we hope to learn in depth about the birth and history of our particular solar system, and of our own Earth.

We expect to learn about the evolution of the planets from their initial formation to their present status, and about the phenomena and the forces that shape planetary environments. By understanding the histories of the planets and the reasons for their diverse present-day conditions we simultaneously increase our understanding of Earth. As our conscious influence on our own Earth—no longer negligible—grows rapidly larger, it is essential that we build a confident understanding of the behavior of terrestrial environments.

We expect to learn about the conditions which gave rise to the appearance and successful evolution of life in the solar system. Eventually we hope to ascertain the prevalence of planets in the universe as well as the prevalence of habitable planets, and perhaps, life.

We expect to learn how the laws of nature shape the universe in which we live. Through scientific exploration of the solar system we extend direct human experience to encompass the largest accessible physical system. This allows us to observe, first-hand, a broad range of important natural phenomena that cannot be studied in our laboratories. The solar system is a vast, natural "laboratory" in which

we can examine physical processes such as planetary tectonics, global atmospheric circulation, large-scale chemical evolution, the behavior of orbiting ring and disk systems, and the dynamics of astrophysical plasmas.

The History of Matter

The solar system is a relatively recent arrival in the universe. Its formation and evolution are parts of a process that began with the origin of the universe and continues even today.

According to our present ideas, the universe as we know it began some fifteen billion years ago, expanding from a hot, dense state in an event known as the Big Bang. Extrapolating our understanding of matter back to the earliest moments of the universe, we believe that only the simplest forms of matter emerged at the universe's birth—hydrogen and helium for the most part. Most of the material essential to the formation of planets and the existence of living forms was absent.

The self-confining, gravitational force of large clumps of matter apparently was sufficient to overwhelm even the universe's early expansion; localized gravitational collapse produced the first generation of stars, star clusters, and galaxies. In their hot, high-pressure and high-density interiors, stars produce energy through the fusion of low-mass atomic nuclei to higher mass nuclei. In normal stars like the Sun, hydrogen nuclei are joined together to make helium, in a process that liberates large amounts of energy.

A star like the Sun can persist in its normal state, deriving energy from the fusion of hydrogen to helium, for some ten billion years. Upon the inevitable depletion of its internal, hydrogen-based energy source, a star proceeds through more advanced evolutionary stages in which it converts successively more massive nuclear species into yet higher mass nuclei, to satisfy its needs for energy and to prevent collapse under the influence of its strong self-gravity. After converting hydrogen to helium, it proceeds to convert the helium to carbon and oxygen, then to silicon-like nuclei, and so on until, in the more massive stars, the nuclear fusion products approach the mass of iron nuclei. Beyond this point no further energy can be extracted by building nuclei of increasing mass. Atomic nuclei with masses near that of iron are the most stable of nuclei; conversion of these nuclei to other species, through either nuclear fusion or nuclear fission, requires not the extraction of energy but the injection of energy.

Having depleted all of its nuclear energy sources, a star begins to cool and can no longer resist the pull of its own gravity. In the more massive stars, we believe that this process leads to a sudden catastrophic collapse. The gravitational collapse of the star's interior is thought to release a large amount of energy which, flowing from the star, blows the star's outer layers away into space, to disperse and mix with the interstellar matter. At the same time, the exploding material in the ensuing supernova explosion is compressed and heated to the point that fast nuclear reactions occur, resulting in a build-up of very massive atomic nuclei, which are dispersed with the star's outer layers, into the preexisting interstellar matter.

By cooking in the interiors of generations of stars, in between its periodic dispersal by supernova outbursts, the original hydrogen and helium mixture of cosmic matter gradually accumulates more and more of the heavier atoms, including all of the naturally occurring elements. By about four and a half billion years ago—some ten billion years after the birth of our universe—a few percent of cosmic material had been processed into heavy nuclei, including carbon, oxygen, and all of the chemical elements of which we and our environment are composed. The processes by which an interstellar cloud, composed of this cosmic gas and dust, evolved into the stars and planets that we presently observe, the physical processes which govern the present behavior of planets and the processes by which life came into existence, evolved, and helped to create for itself a comfortable planetary environment, are the major subjects of the planetary science program.

The Formation of the Solar System

The collapse and fragmentation of dust and gas clouds to form stars is a continuing process in the interstellar reaches of many galaxies including our own. Many large, cool interstellar clouds are barely able to support themselves against the inward pull of their own gravity. Disturbances such as the passage of a cloud through the gravitational field of a galactic spiral density wave, the collision of one cloud with another, or compression induced by the passage of a supernova-induced blast wave, may precipitate the sudden collapse of such an interstellar cloud. There is at least evidence that a nearby supernova may have been responsible for precipitating the formation of our own solar system.

All interstellar clouds contain large amounts of angular momentum by virtue of their individual motions as well as their general rotation with the galaxy. Like a spinning ice skater drawing in her arms, gas falling toward the rotation axis spins all the faster. Some evolutionary paths probably lead to multiple star systems with the angular momentum distributed in the mutual stellar orbits. In other cases, and apparently in the case of our solar system, the path leads to the formation of an extended disk. The Sun and planets were apparently born simultaneously and as parts of the same process. Gas and dust from a collapsed interstellar cloud formed a rotating accretion disk. Dissipative forces—as yet barely understood—resulted in the net outward motion of most of the angular momentum and the inward motion of at least much of the mass. Most of the retained mass aggregated in the center to form the Sun. Small amounts remained in orbits about the Sun and subsequently formed into the planets, satellites and minor bodies we see today. The ratio of the mass retained in the solar system to the mass lost from it remains a matter of speculation because we understand little about the transfer of mass and angular momentum.

It is believed that this proto-planetary/proto-solar disk was hot in its central regions and considerably cooler near its periphery. Temperatures in the disk may have ranged from several thousand degress Kelvin to only one or two hundred degrees above absolute zero. Large variations in density and pressure certainly existed also.

The rate and character of chemical reactions are highly sensitive to these thermodynamical quantities; particularly sensitive is the condensability of various chemical compounds and minerals. In the high-temperature inner regions only the most refractory materials—like metals and metallic oxides—could condense out of the gas. Proceeding outward, toward cooler and cooler temperatures, successively more volatiles—like water and methane—could condense from the gas. In the coldest outer regions of the nebula, virtually all of the matter except gaseous hydrogen, helium, and neon could have condensed into solid forms. The general variation in planetary compositions follows this condensation sequence with regard to their distance from the Sun: planets of rock and metal near the Sun; planets with much larger abundances of gas and ice in the outer solar system.

The accumulation of condensed material into planets may have involved accretion and localized gravitation collapse and mutual collisions. However, our present ignorance of conditions in the primal nebula, and of how a multitude of bodies interacts, makes it difficult to develop reliable theories. There may have been a succession of steps building larger and larger bodies by the accretion of numerous smaller ones. Molecules and dust may have simply stuck together as they settled toward the pancake-like midplane of the nebula. As successive layers of dust became ever more concentrated, they probably became unstable, leading to the formation of planetary building blocks called "planetesimals," several kilometers in diameter. Subsequent collisions led to ever larger planets. In the late stages of growth, a planet's gravity may cause the hydrodynamic collapse of the surrounding nebular gas onto the core planet, accounting for the deep, gaseous envelopes around the Jovian planets.

According to these accretion scenarios, the small, primitive bodies that we still observe in the solar system—the asteroids and comets—are leftover pieces of planetesimal material that escaped incorporation into planets or large satellites.

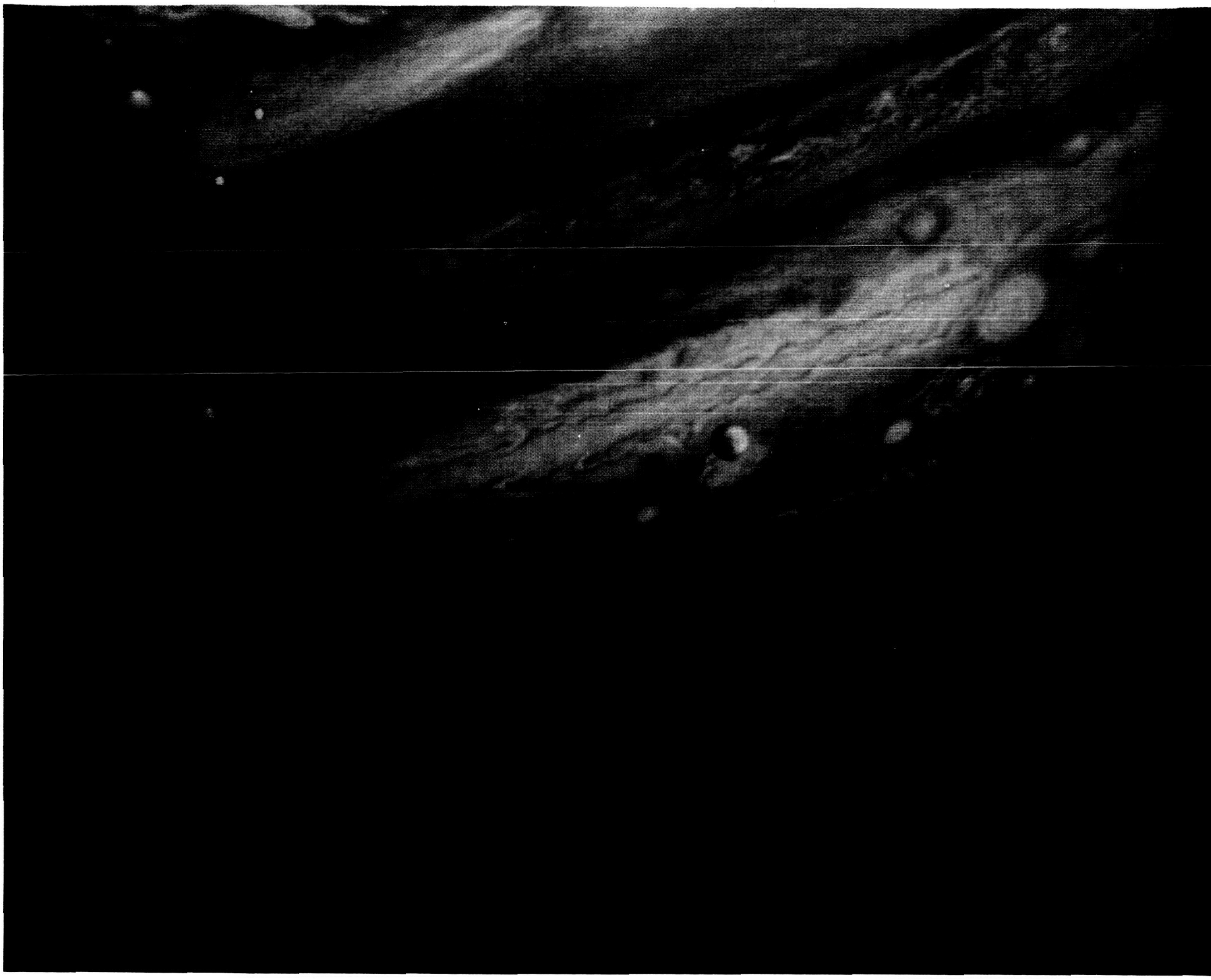
Other theories suggest, instead, that in a very massive nebula, hydrodynamic instabilities produced giant, gas-rich protoplanets, and that these were the progenitors of all the planets. According to these ideas the main difference between the planets of the inner and outer solar system is that the inner ones had their massive gaseous envelopes stripped from them, perhaps by a tremendous expulsion of radiation from our Sun. We can distinguish between these models by means of observations of planetary composition.

The Solar System

Briefly, the solar system consists of ten major bodies and a large number of secondary objects. Most of the mass in the solar system resides at the system's center in the Sun. Solar material is thought to be closely representative of average cosmic material in composition. The Sun's radius, some 690,000 kilometers, is about one hundred times that of Earth.

The planets are arrayed about the Sun in roughly circular and coplanar orbits near the Sun's equatorial plane. These planets can be divided into two broad classes: the inner, or terrestrial, planets and the

Two of Jupiter's moons transit the planet: Io (left), about 350,000 km above the planet's Great Red Spot, and Europa (right).



outer, or Jovian, planets. The terrestrial (Earth-like) planets consist primarily of rock and metal with no gas or only a small amount in a thin, outer, atmospheric layer. Typically, each terrestrial planet is several thousands of kilometers in radius and contains about one-millionth the mass of the Sun. The terrestrial planets occupy the inner part of the solar system, circling the Sun at distances ranging from sixty to more than two hundred million kilometers from the center.

Although roughly similar in size, mass, composition, and distance from the Sun, the four terrestrial planets vary widely in ways that are striking and important to us as living creatures, dependent on a narrow and potentially fragile range of environmental conditions. Only Earth has the supportive combination of temperature,

atmosphere, and abundant liquid water necessary to sustain advanced life. By contrast, the natural environments on Mercury, Venus and Mars are hostile, dangerous places. Mercury has virtually no atmosphere. The high level of solar ultraviolet radiation that bombards the Martian surface evidently precludes living organisms. Mars' hostile environment apparently prevents even the sustained presence of nonliving organic matter. The dry surface of Venus, blanketed with an atmosphere one hundred times as massive as Earth's, traps solar radiation so efficiently that its temperature is near the melting point of lead. Both Mars and Venus have large features on their surfaces, including volcanos, valleys, mountains and elevated plateaus.

Over the last decade, studies of Mars and Venus have indicated apparently large past changes in their surface environments. The surface of Mars reveals large erosional features which suggest the prior presence of large amounts of flowing water. The scale of the features seems to require the water to have been recycled in a hydrologic cycle that may have involved rainfall over long periods of time—a condition far different from Mars today. The large abundance of the hydrogen isotope deuterium in the present atmosphere of Venus suggests that great quantities of water once existed on Venus, perhaps in the form of oceans. Though the process is poorly understood, it appears that this once perhaps Earth-like planet underwent an environmental catastrophe that boiled off this water.

These new discoveries have awakened our appreciation for the susceptibility of terrestrial environments to large evolutionary changes. Venus, Earth, and Mars provide natural laboratories for investigating the nature and the causes of change in terrestrial environments. Detailed comparisons of these worlds will greatly advance our understanding of the Earth and its early history.

The Jovian (Jupiter-like) planets occupy the outer part of the solar system at distances from the Sun far greater than those of the terrestrial planets. Jupiter orbits at some 780 million kilometers, while Neptune orbits at some 4,500 million kilometers. The Jovian planets are far more massive than the terrestrial planets, as much as one one-thousandth the mass of the Sun. And they are proportionately larger, with radii as much as one tenth that of the Sun. In composition, the Jovian planets are much more like that of the Sun than are the Earth-like planets, yet there appear to be differences among them. All have rocky cores mantled by hydrogen and helium and trace amounts of volatile species such as methane, ammonia, and water. Jupiter and Saturn have thick hydrogen and helium atmospheres with traces of methane, ammonia, and water in near relative solar abundances. On the other hand, the hydrogen and helium atmosphere of Uranus appears to be relatively enriched in methane. The same may be true for Neptune.

Pluto, the most distant of the planets, moves about the Sun at a distance of about 5,900 million kilometers. This small, enigmatic planet may be in a class of its own or may resemble the moons of the Jovian planets.

The overall structure of the solar system exhibits important regularities that apparently reflect systematic aspects of the formation

processes. These provide important clues about the solar system's birth.

There are a wide variety of satellite systems (moons) associated with many of the planets. The largest satellites in the solar system are roughly the size of Earth's Moon or the planet Mercury, but there are many others ranging downward in size to just chunks and bits of inert debris.

The best developed satellite system circles Jupiter. The four Galilean satellites—so named because of their first discovery by Galileo—all are planetary-scale bodies. The two inner satellites, Io and Europa, consist dominantly of rocky, high-temperature condensate material, roughly similar to the composition of the terrestrial planets. In contrast, the two outer satellites, Ganymede and Callisto, are rich in water, which condenses at a much lower temperature than do rocky materials. Conceptually, the structure of Jupiter's system of Galilean satellites mirrors the variation in planetary composition with distance from the Sun. The formation of this miniature solar system may well be an analogue to the formation of the entire solar system.

The satellites pose important scientific problems and challenges of their own. Our own Moon is sufficiently different from Earth that accounting for its origin and emplacement in orbit about Earth is a special challenge. Saturn's largest moon, Titan, with its nitrogen-methane atmosphere, possibly with liquid methane seas, is an important laboratory in which to explore elements of natural organic chemistry, similar to that which presumably preceded the onset of life on Earth. The remarkable geological activity of some of the cold, outer planet satellites—for example, Io's active sulphurous volcanic eruptions—is a challenge to our understanding of how planets behave and where they get their internal heat.

In addition to the planets and their satellites, the solar system contains numerous small, primitive objects—the asteroids and comets. Asteroids are largely, though not entirely, confined to an orbital belt that lies between Mars and Jupiter. Telescopic observations indicate that asteroids are composed mostly of rock and metal. However, asteroids near the outer edge of the belt have increasingly larger abundances of volatile material such as carbon and water. As in the case of the planets themselves, the variation of asteroid compositions from the inner part to the outer part of the belt probably reflects variations in the conditions of the asteroids' formation.

Asteroids exist in a wide variety of sizes. The largest are of the order of 1,000 kilometers across. The smallest visible asteroids (among those whose orbits intersect that of Earth) are hundreds of meters across. Many asteroids are believed to be fragments remaining from collisions between larger objects; others are though to be planetesimals that never aggregated into planet-sized objects, possibly because of the large, disruptive gravitational influence of neighboring Jupiter. Some asteroids also are thought to reside in space near where they were formed.

Comets are small clumps of ice and dust that orbit in a halo or "cloud" that extends more than fifty thousand times as far from the Sun as Earth. Some theorists believe that comets originally formed much closer to the Sun, perhaps near Uranus or Neptune. In fact, they

Comet Kohoutek in 1974

may be the remnant building blocks for those planets. Subsequent gravitational deflection moved them out to their present large distance from the Sun.

The gravity of passing stars occasionally sends one of these comets near the Sun. There, warmed by solar radiation, the comet emits large quantities of gas and dust and develops its spectacular, extended, fan-shaped tail. Spectroscopic measurements made during this outgassing phase have revealed the presence of a wide variety of simple organic molecules. Since the gaseous molecules we can observe using telescopes are thought to be fragments of more complex molecules that have been broken apart by solar ultraviolet radiation,

we can, at present, only speculate on the complexity of the "parent" molecules that are released from the heated cometary nucleus. The contribution that comets, colliding with the Earth billions of years ago, may have played in seeding our planet with organic molecules is also a matter of speculation at this time.

While close to the Sun, the orbits of comets are disturbed by the gravity of the larger planets. Some comets are then ejected from the gravitational control of the solar system, never again to approach the Sun. Others are captured into tightly bound, short-period orbits and reappear frequently in the inner solar system.

Comets may well constitute the best preserved samples of nebular condensates from the time of the solar system's formation. The volatile, icy matter that they still retain indicates that they formed originally in a cold environment. Pristinely stored for billions of years in the deep freeze of nearby interstellar space, they lose virtually none of their matter until they approach the Sun. Investigation of comets may well provide our most significant information about the original chemistry of the solar system and the extent to which cometary matter may have been involved in the processes leading to life on Earth.

The comets and many of the asteroids never aggregated into objects of planetary size. Because they remained small, heat escaped easily from their interiors; internal temperatures never rose to high values in many of these small bodies and most planetary evolutionary processes never occurred. Thus, these primitive objects remain nearly unchanged since their formation some four and a half billion years ago. Telescopic evidence and information gleaned from asteroidal and cometary fragments, which fall to the Earth as meteorites, tell us that some asteroids (and possibly some comets) did indeed undergo substantial evolution early in their lives. In these cases, the evolutionary processes may have involved energy sources long since exhausted and no longer active in the present solar system. Thus, even the evolved asteroids may preserve evidence, which exists in no other place, of phenomena and processes from the early solar system.

Comets and some asteroids are distinguished from the planets in that they are primitive, unprocessed objects. The planets formed with large stores of internal energy—gravitational energy trapped during their original accretion and energy stored in radioactive nuclei for later release. The large size of planetary bodies, and their consequent small surface areas in comparison with their masses, inhibits the escape of internally released energy, forcing increases in the interior temperatures. Because of this, planetary interiors typically reach high temperatures, and the escaping heat drives evolutionary processes. The evolved planetary material, repeatedly heated over time, bears little resemblance to its physical and chemical state at the time of the solar system's formation.

Planetary Processes

Although the larger bodies retain few clues about solar system formation, records of subsequent, planetary evolution are scattered throughout the solar system. The earliest parts of these records are mostly erased from the Earth but are still accessible in the landforms and materials on the surfaces of the Moon, Mars, and Mercury. Likewise, the surfaces of satellites of the outer solar system hold records of the changing space environment and internal evolution of bodies in that region. These geologic records are in the form of chemical and isotopic fingerprints as well as in the stratigraphic sequences, structural relationships, and morphology of the landforms. One of the richest potential contributions of planetary research is the careful reconstruction of the geologic histories of the planets, including an understanding of internal and external processes that have controlled their evolution. One of our ultimate goals is to lay out the sequence and controlling factors of the Earth's evolution along with that of its attendant life.

The key to understanding these records—to reconstructing the sequence of evolution of the planetary interiors, crusts, and atmospheres—lies in understanding the natures and rates of the physical and chemical processes that modify planets. Such processes fall into two categories, according to their characteristic energy sources, termed ***endogenic*** and ***exogenic.*** Exogenic processes are those caused by forces outside or external to the planet. Some examples are the solar radiation that drives atmospheric systems; tidal flexing of planetary crusts like the one that drives Io's volcanoes; and the torrential impact of solar system debris onto planetary surfaces early in their histories. Endogenic processes arise from energy sources internal to the planets. Heat generated by the radioactive decay of uranium, potassium, and thorium or by rearrangements of mass in the planetary interiors are examples.

Our view of the possible range of diversity of planetary processes has been expanded immensely by the U.S. planetary exploration program. Step by step, our understanding is progressing. Lunar studies reveal that the Moon's crust records a period of heavy bombardment extending up to about four billion years ago during which the lunar highlands were intensely cratered by remnant debris. This bombardment followed the Moon's initial accretion. Impacts into the lunar crust continued, but at a much lower rate. Following this period of intense bombardment, enormous pulses of volcanism, primarily during the next two billion years, dominated the rest of lunar history. The primary value of studying the crusts of the Moon and Mercury is for the records they provide of early processes long since erased from the Earth. To a large degree we have come to believe that we understand the range of planetary processes that have governed modification and evolution of the planets in the solar system.

The exploration of Mars reinforced the notion that planetary processes, like those found to operate on Earth, are universal. Mars'

surface revealed evidence of volcanic, fluvial, glacial, eolian, and tectonic processes that have led to stratigraphic systems, structural relations, and landforms which are generally understood from a terrestrial perspective. Thus, scientists became further convinced that models for the generation and retention of internal energy were complete. The denser a planet, the greater the amount of radionuclides available to heat its interior. The larger a planet, the greater the ratio of its volume to its surface area; because of this, loss of heat from its interior would be retarded. This model suggested that the Earth should be extremely active geologically; Mercury and the Moon should now be geologically dead; and Mars should be still active, but quiescent relative to Earth. The observations seemed to fit the model.

Armed with this terrestrial perspective, we embarked on the exploration of the outer solar system. Four unmanned spacecraft (two *Pioneers* and two *Voyagers)* were launched in the 1970's to explore the environs of Jupiter and Saturn. We had a reasonably good idea of the compositions of the Galilean and Saturnian satellites, objects that range from rocky bodies similar to the Moon, to large ice-balls mostly made of water that range up to the size of the planet Mercury. Even so, there was no way of imagining the surprising diversity of geologic phenomena found there. We discovered that even at the extremely low temperatures in these environments, tiny, icy moons like Saturn's Enceladus—about 1/100,000th the mass of Earth—can exhibit levels of geologic activity as great as those found on the large terrestrial planets. Jupiter's moon, Io, afforded the Voyager spacecraft spectacular displays of more than ten active, volcanic plumes. Aside from Earth, these are the only other active volcanoes known to exist in the solar system. The youthful and nearly crater-free appearance of Europa's frozen ocean surface suggests that this moon also is geologically active. Here, warm liquid water may exist at shallow depths. Ganymede's bizarre tectonic history may be the analogue of Earth's continental plate tectonics, but on a frozen, half-water world. Saturn's Enceladus shows crater-free patches bounded by ridges, perhaps evidence of internal convection. Iapetus' black and white hemispheres still elude comprehension. Rhea and Dione exhibit strange, braided markings. Evidently even these bodies had complex internal processes early in their histories.

We had no expectation of the complexity of worlds we would discover in the frigid outer solar system simply because the base of information about planetary energy sources was too narrow, and the knowledge about mobility of planetary interiors at such cold temperatures and about types of processes possible was too limited. Tidal heating mechanisms and lubrication of planetary interiors by methane, sulfur, and ammonia are processes we are now examining and think to be commonplace.

Planetary science has been forced to acknowledge the important lesson that, no matter how advanced our scientific judgments, we cannot anticipate the complexity of the universe. We must go out and explore it. Although our progress to date has been dramatic, the frequency with which new discoveries force revision of our models requires us to acknowledge the still immature state of our understanding of the solar system.

Planetary Science Highlights

The science highlights that follow have been selected to provide only a flavor of the excitement of the last 20 years of U.S. planetary exploration. These highlights do not attempt to provide a complete picture nor even a historical perspective.

Mariner 10 Mercury Science Highlights

(Three flybys in 1974-75.)

- Surface heavily cratered, resembling lunar highlands.
- Large impact basin (Caloris) about 1,300 km in diameter.
- Unique planetary feature present: long scarps of cliffs, apparently produced by crustal compression.
- Planet has internal magnetic field, similar to but weaker than Earth's and able to form a true magnetosphere.
- Virtually no atmosphere present (less than 10^{-15} of Earth's); trace of helium discovered, possibly coming from crustal outgassing.

Viking Mars Science Highlights

(Detailed study with the Viking *landers and orbiters commenced in 1976; one of the landers gathered meteorological data until late 1982.)*

- No definite evidence for biological activity in soil, despite unusual chemical reactions produced in life-detection experiments.
- Surface rocks resemble basalt lava; surface chemistry resembles altered basalt.
- Polar cap in north made largely of water ice, with lesser amounts of "dry ice" (frozen carbon dioxide); composition of southern cap may be different.
- Isotopic ratios of carbon and oxygen in atmosphere resemble those in Earth's atmosphere.
- Loss of nitrogen to space has produced nitrogen isotopic ratios on Mars that are different from those on Earth; the heavy nitrogen isotope (N^{15}) has been preferentially retained.
- Abundant erosional channels on surface suggest that Mars could have had a denser atmosphere in the past and may have had liquid water on its surface.
- Noble gas abundances (argon and neon) suggest Mars has a lower volatile content than either Earth or Venus.
- Red color of surface due to oxidized iron.
- Soil is fine-grained and cohesive, like firm sand or soil on Earth.
- Water and sulfur compounds present in soil.
- Small-scale landforms formed by aeolian (wind) processes.
- Surface temperatures range from about −84°C (−120°F) at night to about -29°C (-20°F) in the afternoon.
- Surface pressure of atmosphere (only about 0.8 percent that of Earth's) varies seasonally in accord with sublimation of the polar caps.
- Martian moons (Phobos and Deimos) are grooved, indicating that incipient fracturing has occurred; they are heavily cratered and may be captured asteroids.

Apollo Lunar Science Highlights

(Six manned Apollo *landings from 1969-1972.)*

- A complex, evolved planet; not primordial.
- Moon has preserved early planetary history: extensive primordial melting, catastrophic meteorite impacts, major volcanic eruptions.
- Moon formed 4.6 billion years ago, together with Earth and rest of solar system.
- Moon rocks range from 3.0 to 4.6 billion years old. Most are older than any preserved Earth rocks.
- Three basic rock types: (1) volcanic lavas (maria), (2) aluminum-rich crustal rocks (highlands), (3) unusual KREEP lavas enriched in radioactive elements.
- Lunar surface material ("soil"), a layer of powdery rubble 10-100 m thick, formed by continuous meteorite impact.
- Moon slightly egg-shaped; small end points toward Earth.
- Differentiated interior: outer crust, inner mantle, possible core (metallic?).
- Outer crustal portion (lithosphere) lacks evidence of terrestrial plate-tectonic motions. A different style of planetary development.
- Moon not seismically active; only weak moonquakes.
- Moon rocks generally like Earth rocks, but deficient in volatile elements (hydrogen, sodium, potassium, etc.); not like meteorites.
- Fossil magnetism found in lunar rocks; origin still unexplained (lunar core dynamo? early active Sun? meteorite impacts?).
- Solar wind samples collected from lunar soil; exhibit higher hydrogen to helium ratio than Sun itself.
- Ancient solar wind samples collected; major variations in amount and isotopic composition of solar wind nitrogen over past 1.5 billion years—remains unexplained.
- No major variations in solar flare intensity and particle composition apparent over last 100,000 years.
- No major variation in galactic cosmic ray flux striking lunar surface for approximately last one billion years.
- No evidence of life, past or present.

Pioneer Venus Science Highlights

(Four probes entered the atmosphere in 1978; the orbiter is still operating.)

- Atmospheric composition refined: about 96 percent carbon dioxide, four percent nitrogen, and minor amounts of water, oxygen, and sulfur compounds. Pattern of noble gas abundances confusingly different from those of Earth and Mars.
- Atmospheric enhancement of heavy hydrogen isotope (deuterium) implies loss of water—at least meters deep—from the planet's surface sometime in the distant past.
- At least four distinct cloud and haze layers exist at different altitudes above the surface.
- Haze layers contain small aerosol particles, possibly droplets of sulfuric acid.
- Atmosphere circulates in large planet-wide systems; much simpler than Earth's atmospheric circulation.
- Collar of polar clouds discovered, may be part of large polar vortex in atmosphere.
- Radar altimeter observations reveal two broad plateaus rising above Venus' surface, as well as apparent volcanic structures, craters, and canyons.
- Lightning and thunder present; first detected by Soviet *Venera 11* and *12* landers (1978), confirmed by *Pioneer*.

Voyager Jupiter Science Highlights

*(*Voyager *1 and 2 encountered Jupiter in 1979.)*

- A thin, planetary ring discovered; much narrower than Saturn's, made of much smaller particles.
- Four Galilean moons imaged in detail; a remarkably varied geology found.
- Io, the innermost moon, had at least 10 active volcanoes, some of which changed in appearance between the two *Voyager* encounters; surface material probably powdered sulfur, with some sulfur dioxide.
- Heat source for Io's remarkable volcanic activity believed to be dissipation of tidal energy, a proposal made just a few weeks before the first *Voyager* encounter.
- Another moon, Europa, is covered with a frozen ocean, perhaps liquid at great depths.
- Ganymede, found to be the largest moon in the solar system, showed evidence of geological activity analogous to plate tectonics on Earth.
- Jupiter's clouds photographed in great detail; planetary winds tracked.
- The Great Red Spot rotates in a complex manner; the overall direction is anticyclonic, indicating that it is a huge high-pressure area.
- The presence of methane, ammonia, water vapor, and a few more complex molecules in the atmosphere confirmed.
- Helium abundance found to be 11% by ***volume*** (approximately 20% by mass), very close to that of the Sun and other stars.
- Magnetosphere is the largest object in the solar system, 15 million km across, 10 times the diameter of the Sun. Contains the normal ions of hydrogen, but also oxygen and sulfur, evidently ejected from the moon, Io.
- A much denser region of ions occupies a *torus* surrounding Io's orbit. It emits intense ultraviolet radiation and also generates auroras at high latitudes on Jupiter.
- These auroral phenomena are linked to strong radio emissions that were discovered from Earth more than 20 years ago; strong electric currents, flowing along the Jovian magnetic field lines, were observed.
- In addition to a planetary aurora—apparently due to the Io torus— huge lightning flashes and meteors photographed on Jupiter's night side.

Voyager Saturn Science Highlights

*(*Voyager 1 *and 2 encountered Saturn in 1980 and 1981.)*

- Rotation period determined by radio emissions to be $10^h\ 39^m\ 15^s$.
- Helium content of upper atmosphere about 6 percent (by ***volume),*** contrasted with about 11 percent for Jupiter. Missing helium may exist as precipitated liquid in the interior.
- Internal heat source of Saturn, relative to the planet's mass, is even larger than that of Jupiter, perhaps because of heat released from precipitating helium inside.
- Minor components in atmosphere include: ammonia (NH_3), methane (CH_4), phosphene (PH_3), ethane (C_2H_6), acetylene (C_2H_2), methylacetylene (C_3H_2), and propane (C_3H_8).
- Atmospheric details similar to Jupiter; alternating light/dark bands and circulating storm systems.
- Wind speeds up to 1,500 km/hr (1,000 mph) measured near equator; these winds are four to five times faster than those on Jupiter.
- Unusual atmospheric features include: ribbon-like wave features, large and small clouds, and a red oval similar to but smaller than Jupiter's Red Spot.
- Aurorae observed in atmosphere above Saturn's poles; extensive ultraviolet emission at lower latitudes.
- Six previously known rings are actually composed of innumerable, individual ringlets; very few gaps exist anywhere in ring system.
- Elongated radial features ("spokes") observed in B-ring, apparently co-rotating with ring.
- Complex dynamical effects seen in rings, including spiral density waves similar to those believed to generate spiral structure in galaxies.
- Thin, outer F-ring composed of three distinct, but intertwined ringlets. Two small moons apparently act as "shepherds" to keep ring in place.
- Eight small moons discovered, some co-orbital, some acting as "shepherds" to F and A rings.
- Inner moons (Mimas, Tethys, Dione, Rhea) apparently formed of ice; they display heavily cratered surfaces like the Moon and Mercury. Some moons (Dione, Rhea, Tethys, Enceladus) show evidence of internal geological activity (rifts, linear features, smooth, uncratered surfaces).
- Titan diameter measured: 5150 km, slightly smaller than Ganymede.
- Titan atmosphere largely nitrogen with only minor amounts of methane and other hydrocarbons. Surface temperature about -175°C (-280°F). Surface pressure is about 1.6 bars, about 60% greater than surface pressure on Earth.
- Titan's surface may hold large accumulation of liquid methane.
- Of the outer moons, Iapetus shows still-unexplained light and dark-colored hemispheres, while Phoebe has characteristics suggesting that it may be a captured asteroid.
- Saturn's magnetic field is stronger than that of Earth, weaker than Jupiter's. Field is aligned virtually parallel to the axis of rotation of the planet. As at Jupiter, the size of Saturn's magnetosphere is controlled by the external pressure of the solar wind.

Small Bodies Science Highlights

(Information on asteroids has been obtained almost entirely from ground-based observations; comets are studied from the ground, sounding rockets, and Earth-orbiting spacecraft; meteorite samples found on Earth are subjected to detailed laboratory investigation.)

COMETS

- A "cloud" of comets, with an estimated population of 10^{10} to 10^{12}, evidently surrounds the solar system at an average distance about halfway to the nearest star; thus comets are the most numerous class of bodies in the solar system.
- Observed cometary phenomena are best explained by the "dirty snowball" model of the nucleus, in which solid "dust" particles are embedded in a matrix of volatile ices (principally water ice).
- Two new molecules, HCN and CH_3CN, were detected in Comet Kohoutek in 1974; the molecules CO and CS, the ion C^+, and H_2O^+ have been detected by UV techniques as well.
- Comparison of abundances of hydrogen, carbon, oxygen, and sulfur and the metals with their cosmic values shows that helium is depleted by a factor of 10^3, carbon by a factor of four, and the rest are not depleted at all.
- Observations and analysis of molecules found in interstellar space and comets are now interpreted as suggesting strongly that they have a common origin.
- Mass loss of water and possibly other volatiles explains the "nongravitational forces" acting on comets.
- Extraterrestrial dust particles, collected from Earth's upper atmosphere, are a newly available extraterrestrial material and may be of cometary origin.
- Ice grains have been detected in either the coma or tail of several comets.
- Disconnection and loss of the plasma tail has been reported for several comets; plasma waves have been detected in cometary comae and their velocities measured.
- Spin rates have been inferred for a large number of cometary nuclei, and spin-axis orientations have been derived for several short-period comets.
- Discrete dust-emission areas, responsible for a burst-like activity, were detected and mapped on the rotating nucleus of Comet Swift-Tuttle; the recurrent outburst activity of Comet Schwassmann-Wachmann 1 was interpreted as asymmetrical ejection from one or two large areas on the slowly rotating nucleus.

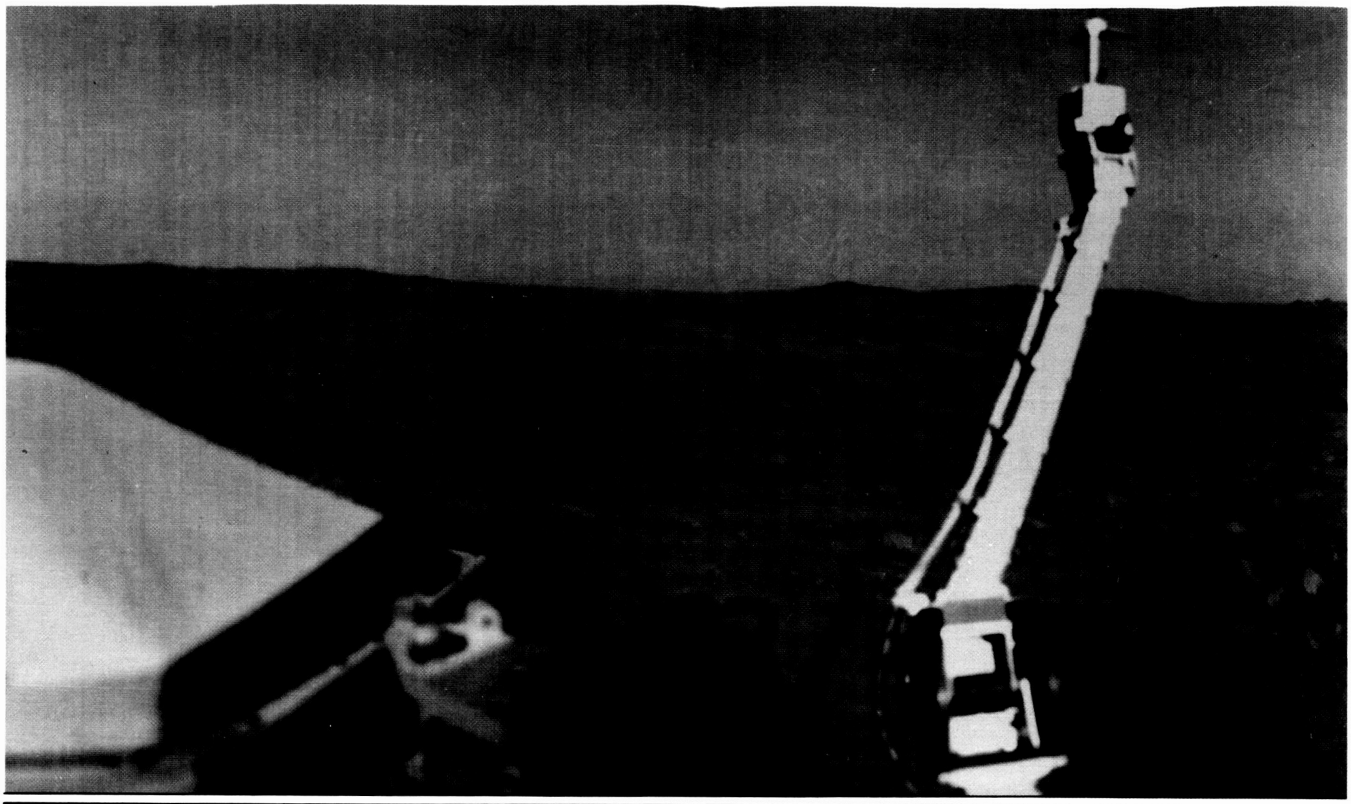
ASTEROIDS

- Approximately 2,000 Mainbelt asteroids have well known orbits and have been assigned names.
- Diameters range from 1000 km (1 Ceres) down to 20 km and probably smaller.
- Beginning in this century, more than 60 asteroids that cross Earth's orbit have been discovered, most of them within the last five years.
- Asteroids are classified on the basis of their spectral characteristics into six compositional families.
- Surfaces of most asteroids appear dark, suggesting significant carbon content. Chemically-bound water detected on some surfaces.
- Surface composition of Vesta (550 km diameter) resembles basalt lava.
- Minor planet Chiron discovered in 1979 between orbits of Saturn and Uranus, far outside normal asteroid belt.

METEORITES

- Meteorites typically spend 10 to 500 million years exposed to space environment, which suggests relatively recent collisions and breakup in asteroid belt during this time.
- Some meteorites are basalts, aged about 4.5 billion years, indicating that early melting occurred on their parent asteroids.
- Meteorites contain daughter products of **primordial, short-lived radioactive elements;** parent elements could have provided radioactive heat for short-term melting when the asteroid parent bodies formed.
- Formation ages of most meteorites (4.6 billion years) provide a firm estimate for the age of the solar system.
- Cooling rates of iron meteorites, determined from their crystal textures, range from 1 to 20 degrees per million years, too rapid for them to have been in the core of a large planet.
- Solar wind gases are found trapped within some meteorites, providing a sample of solar activity in the past.
- Light-colored inclusions, made up of high-temperature minerals, have been found in the Allende meteorite and other carbonaceous meteorites; these may be samples of the first material to solidify when the solar system formed.
- Isotopic anomalies, especially in oxygen, found in light-colored Allende inclusions, suggest that some matter may have been introduced into the solar nebula from another star, presumably a nearby supernova.
- Amino acids of definitely extraterrestrial origin have been found in several carbon-rich meteorites.
- **One meteorite, of anorthositic composition, discovered in Antarctica, is definitely of lunar origin.**

This panoramic view of the Viking 1 *landing site looks northeastward across Mars' Chryse Planitia—the Plains of Gold.*



4. The Era of Spacecraft Exploration

The first interplanetary spacecraft, *Mariner 2,* was launched to Venus just two decades ago, inaugurating an extraordinary era for science and exploration in which we first began to learn the true nature of our planetary neighbors and to develop a perspective of Earth itself as a planet. Because the technological capabilities of these early spacecraft were very limited, the data returned from the first U.S. and Soviet reconnaissance missions to Venus and Mars served to better define scientific questions about these bodies rather than to provide answers. Nevertheless, since our knowledge was so meager, the early missions made many fundamental discoveries and stimulated the growth of a previously neglected observational science—planetary astronomy—which has provided a large share of the discoveries about the solar system made since that time.

At the same time as these unmanned, deep-space probes were being developed, along with the launch vehicles and tracking facilities needed to support them, the U.S. made a commitment to a much larger enterprise, the *Apollo* project to land men on the Moon. This ambitious undertaking had a profound effect on the pace of planetary exploration. The *Apollo* missions, which returned large quantities of lunar rock and soil samples from six sites on the near side of the Moon, permitted a quantum jump in our ability to tackle fundamental

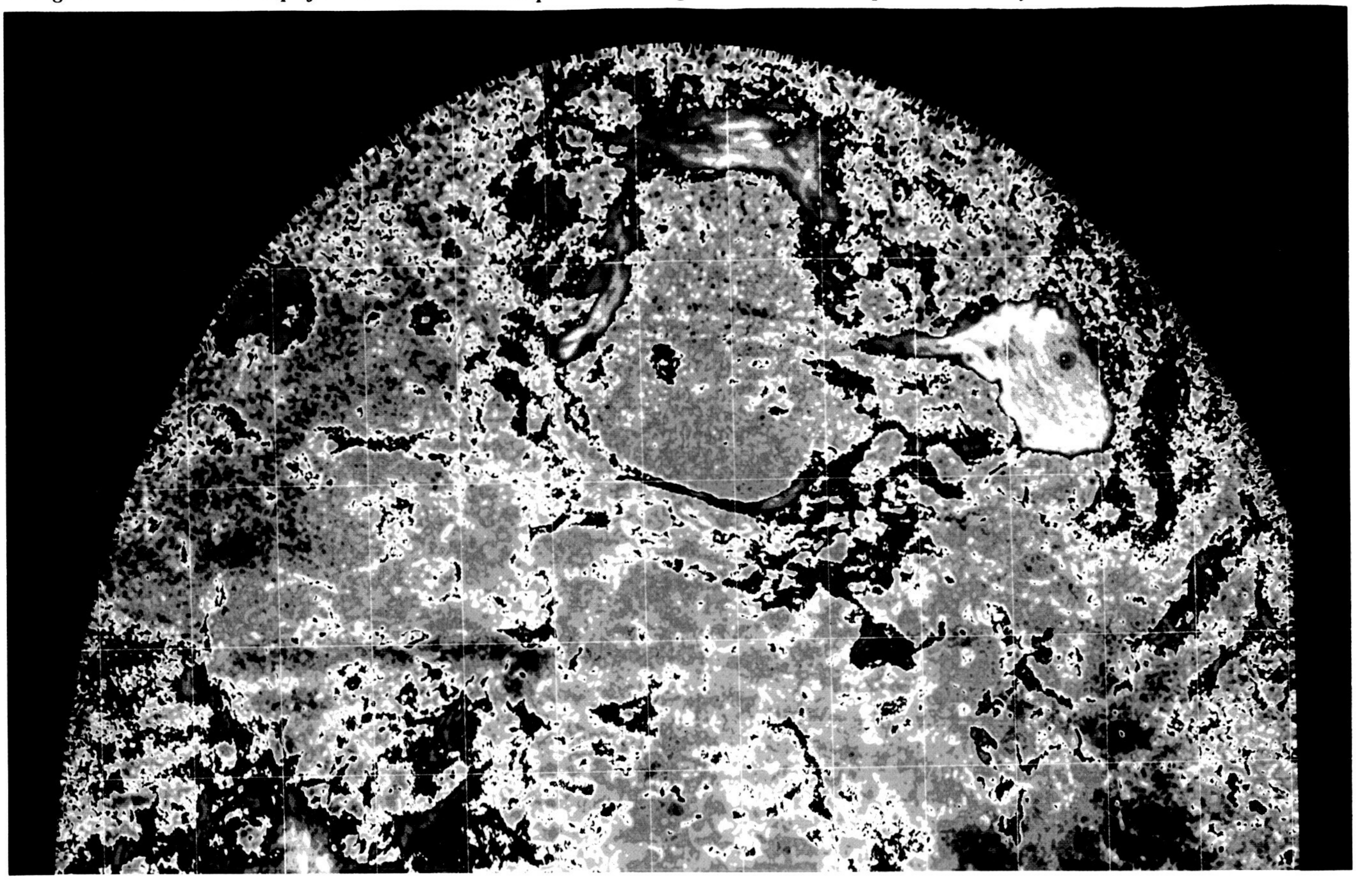
questions about the Moon's evolutionary history. These missions also provided a demonstration of the "ultimate" techniques needed for unmanned planetary exploration—the analysis of returned samples in terrestrial laboratories equipped to make ultra-precise measurements of ever-improving refinement. Such techniques were applied with great success to the analysis of the world's collections of meteorites and of new falls—samples from a great diversity of unknown parent bodies in the solar system—and also to the analysis of lunar samples from unmanned Soviet missions. As a result, the scientific knowledge gained from the analysis of planetary materials—which in recent years includes individual grains of dust collected in the Earth's stratosphere and thought to have originated in comets—has come to be comparable in importance and complementary in nature to that gained from spacecraft missions and telescopic observations.

U.S. planetary exploration assumed a rather different character when the *Apollo* program ended. By that time most of the decisions affecting the planetary program of the 1970's had already been made, decisions that led to a substantial broadening and deepening of scope, which would include reconnaissance missions to Mercury, Jupiter and Saturn and follow-on, second generation missions to Venus, Mars, Jupiter and Saturn. This was a period when the early lunar and planetary discoveries were being assimilated and combined with the newly unlocked secrets contained in meteoritic samples. It also was a time of rapid technological advances.

During this period Mars enjoyed an extremely high priority for exploration because of an exciting untested hypothesis: that living organisms might have evolved on Mars in an environment that was judged more Earth-like than anywhere else in the solar system. This particular exploration imperative stimulated an explosion of technological innovation and provided the justification for the development of a high energy launch capability—the *Titan III-Centaur* combination—sufficient to meet the needs of both the *Viking* (Mars) lander/orbiter project and of the *Mariner Jupiter-Saturn* project. The latter mission (renamed *Voyager),* was planned to follow the outer planet pathfinder missions of *Pioneers 10* and *11* and to take advantage of a rare alignment of the outer planets which allowed use of the gravity swing-by technique to achieve short trip times to reach planets beyond Jupiter. The *Viking* and *Voyager* missions proved to be the pinnacles of technological sophistication and scientific success, even though both were significantly scaled-down versions of much more ambitious proposed missions—*Voyager-Mars* and *The Grand Tour,* respectively.

With the second *Voyager* flyby of Saturn in August 1981, the solar system exploration program was at its peak of achievement, a peak that included the recent successes of *Viking, Pioneer Venus (PV)* and *Voyager.* The United States had an active base on Mars until recent months and has one at Venus (the *PV Orbiter).* The *Voyager 2* spacecraft is now on a trajectory taking it from Saturn to Uranus and then to Neptune while three other planetary spacecraft *(Pioneers 10 & 11* and *Voyager 1)* are heading out of the solar system. The latter three spacecraft will be able to investigate the outermost reaches of the solar system where the Sun's influence ends and true interstellar space begins.

This ground-based radar map of Venus' northern hemisphere shows highland areas in red, plains areas in yellow, lowlands in blue.

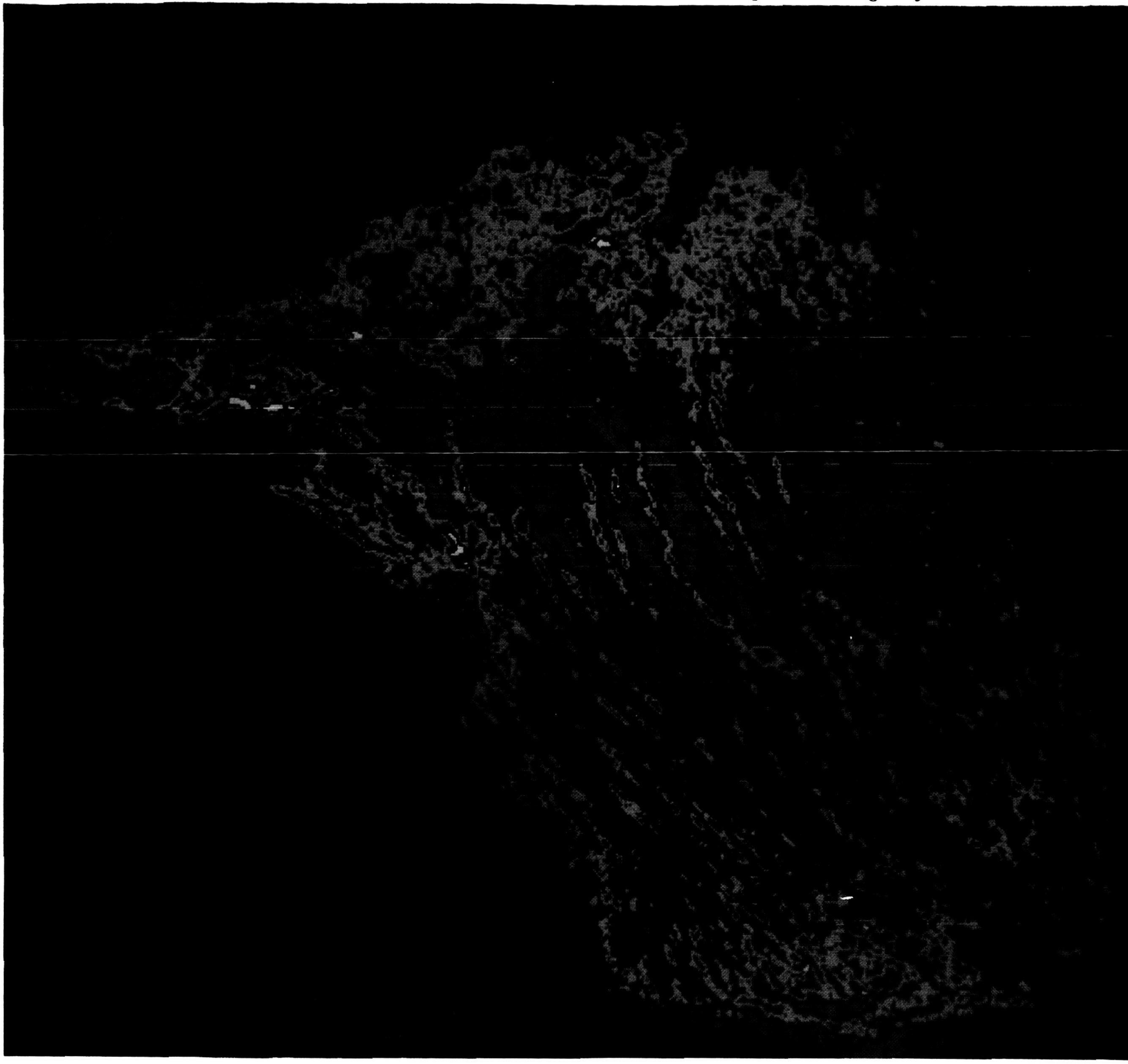


The prospects for the future have been less encouraging, not because of a lack of exciting missions nor because of inadequate technological readiness but rather, because of recent NASA priorities. Only one planetary mission—the *Galileo* mission—is under full-scale development. This mission will place a spacecraft in orbit about Jupiter and undertake an *in situ* investigation of the giant planet's atmosphere using an entry probe. This project is proceeding well (it is now in the hardware fabrication and test phase) despite several schedule setbacks and cost increases resulting from delays in the readiness of the *Space Shuttle* and the required planetary upper stage. Originally planned for launch in 1982, the *Galileo* spacecraft is now scheduled for *Shuttle* launch in 1986 using the *Centaur* upper stage.

The *Galileo* entry probe will make its descent through Jupiter's upper clouds down to a pressure level of at least 10 bars (atmospheres). The orbiter will make multiple encounters with the Galilean satellites during a 20 month tour which will also explore the complex Jovian magnetosphere. Major technological advances have been required by the *Galileo* mission, both for the probe to survive its high speed entry into the massive atmosphere and for the new "dual-spin" orbiter to operate in the intense radiation fields of the giant planet. In both cases success is confidently expected.

One other planetary mission—the *Venus Radar Mapper*—is in an early pre-project phase. It is planned for launch in 1988. This mission, for which the radar imaging team and several other radar and radio

This central region of Venus, called Maxwell Montes, rises higher than Mt. Everest above the planet's average surface.



experiments have already been selected, is designed to provide a global characterization of the Venus surface at high resolution to identify and place in time sequence the geological processes that have been at work since the planet formed. The *Venus Radar Mapper* will fill in the largest gap in our knowledge of the inner solar system and will allow a direct comparison of the evolution of the Earth to that of its "twin" planet, Venus. The principal technological challenge for the *Venus Radar Mapper* lies in the development of the variable incidence angle, space-borne imaging radar system. The success of the Shuttle Imaging Radar (SIR-A) on the second flight of *Columbia* gives confidence that the Venus radar will also perform as required. Like the *Galileo* spacecraft,

the *Venus Radar Mapper* would be launched using the *Shuttle/Centaur* combination. The recent successes of the first five *Columbia* launches have been important milestones for both planetary missions. Another key milestone, however, the successful development of the *Shuttle*-compatible, planetary upper stage, is yet to be achieved.

Like the flight programs, the planetary research and analysis programs were at a peak of productivity and achievement during the 1970's. A large part of this activity is the analysis of data and samples from past missions, an analysis that is being undertaken systematically and in depth at universities, institutes and NASA Centers throughout the nation. This effort attempts to ensure that the investments made in the flight missions are capitalized upon in a scientifically responsible manner. The research programs are also intimately involved in the planning for future missions, so that preparations are being made with a thoroughness not previously possible. In addition, planetary research programs are providing us with a low cost way of learning about aspects of the solar system currently outside our spacecraft technology. Earth-based telescopic observations are still the only means of studying the outermost planets and of surveying large numbers of the asteroids and comets, while meteorite and cosmic dust studies continue to make frequent fundamental discoveries about the nature of the early solar system.

As a result of the austere budgets of recent years, coming at a time of great excitement in the field of planetary sciences, an intense competitiveness has arisen among researchers in all areas so that the quality of the research efforts is exceptionally high. In the face of declining budgets (Figure 5), however, the viability of the planetary sciences research community has been seriously threatened. It is becoming increasingly difficult to maintain balance in the basic research within the various disciplines. The stifling of basic research has had the further result that numerous exciting new opportunities are being bypassed, for example: a serious search for planets about other stars; detailed analyses of newly available samples of interplanetary dust particles and of large numbers of meteorites recovered from Antarctica; a systematic interdisciplinary study of the genesis of terrestrial planets' crusts.

During the last twenty years the United States has been the undisputed leader in solar system exploration. The reconnaissance of the inner solar system has been completed and we have successfully penetrated the asteroid belt with spacecraft that have completed the initial exploration of the two largest of the giant planets. Plans have been made, but not yet put into operation, to initiate the exploration of asteroids and comets. Other countries, however, are ready to offer a significant challenge to the U.S. in this area of planetary exploration. The European nations are entering the field for the first time, as are the Japanese. The Soviet Union appears to be pursuing an aggressive program, as it has in the past, and is expected to conduct a variety of innovative missions over the next decade that will not be limited to its traditional targets, Venus, Mars, and the Moon. Thus, solar system exploration is entering an era of worldwide effort in which the United States must choose whether or not to maintain a leading role.

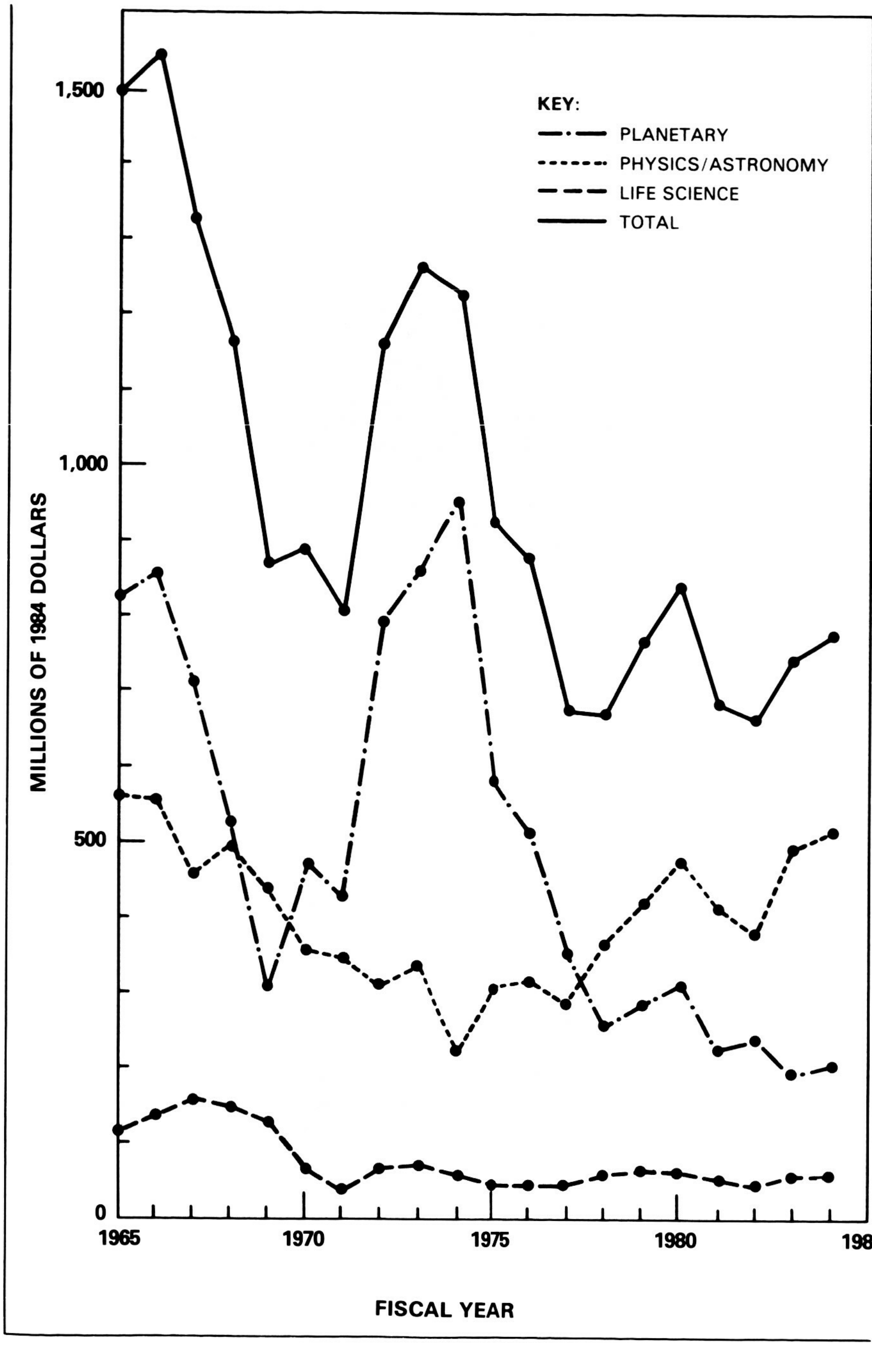
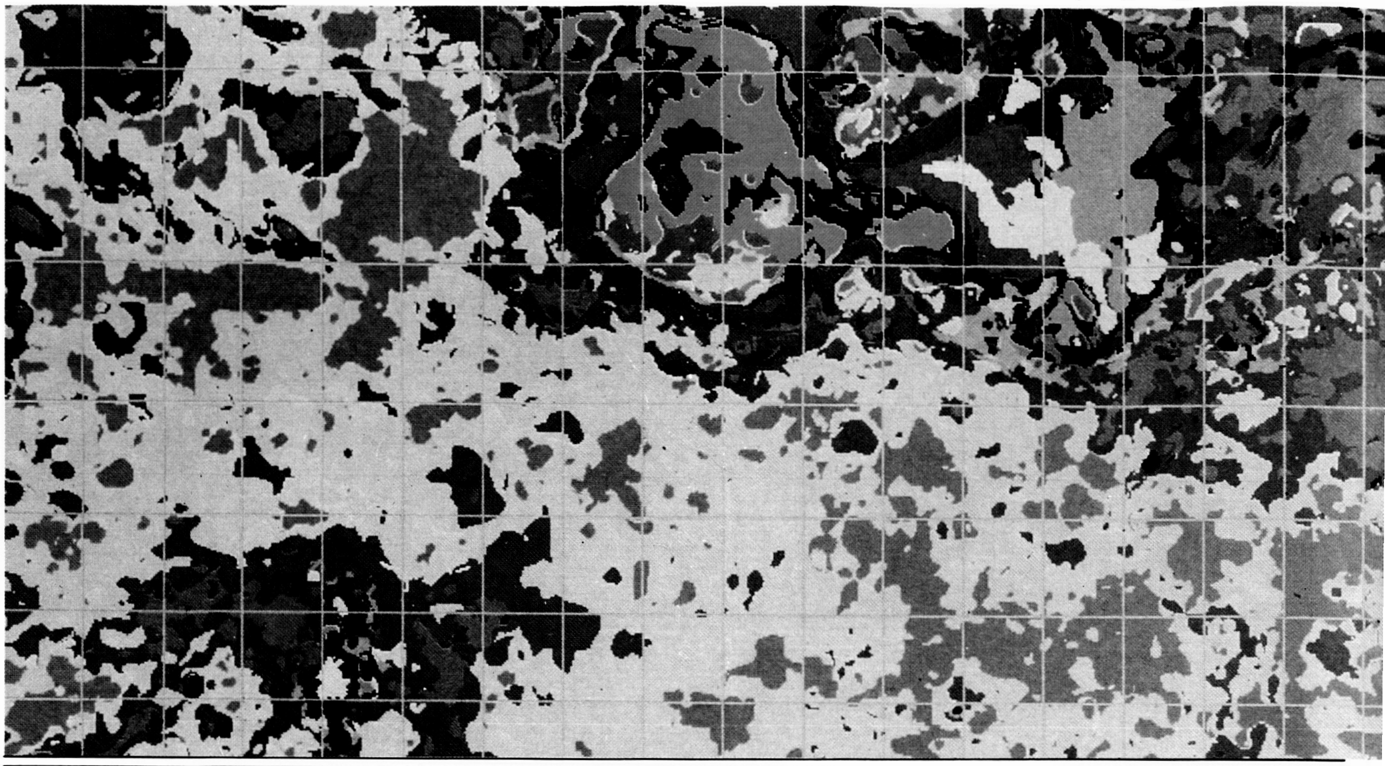


FIGURE 5. **SPACE SCIENCES FUNDING**

This detailed radar map of Venus' northern hemisphere is color-coded according to variations in the planet's surface geology.



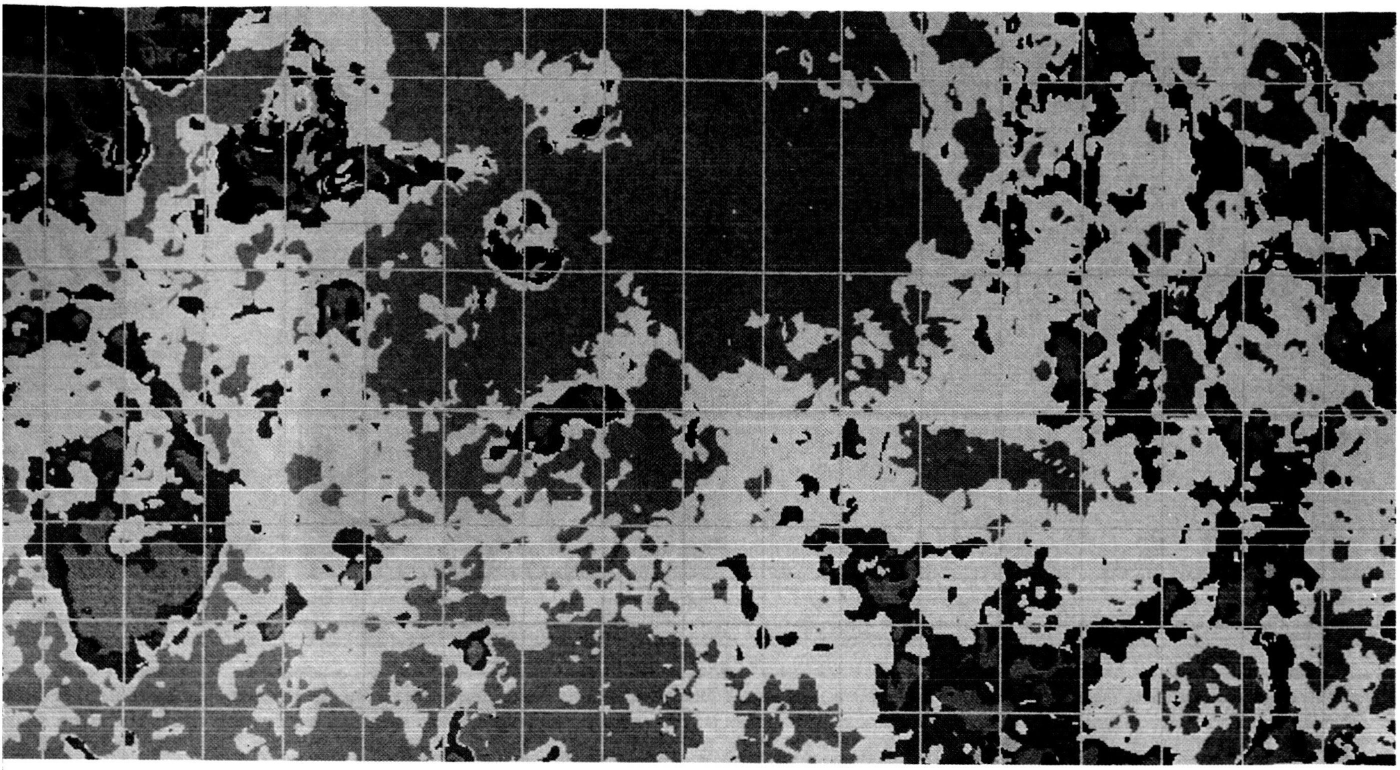
5. Scientific Strategy for Planetary Exploration

During the last several years the U.S. Space Science Board and its Committee on Planetary and Lunar Exploration (COMPLEX) have issued three reports,* each containing a set of recommendations which deal with various parts of the planetary exploration program. NASA has relied extensively on these recommendations.

Largely for reasons of convenience, but also because there are natural divisions, COMPLEX separated its consideration of the solar system into three parts: the inner planets, the outer planets, and the primitive bodies (asteroids and comets). The three reports are viewed as having equal priority in shaping the scientific basis for the planetary exploration program. Part of the policy on which the Space Science Board has based its recommendations is that the "program of planetary investigations should be balanced, i.e., that it should move forward on a broad front to all accessible planetary bodies beginning with reconnaissance, into exploration of selected planets, and lastly to intensive study of a limited number of cases."

The remainder of this section outlines the main points of the Space Science Board/COMPLEX science strategy for planetary spacecraft investigations.

* *Report on Space Science 1975; Strategy for Exploration of the Inner Planets: 1977-1987; Strategy for Exploration of Primitive Solar System Bodies - Asteroids, Comets and Meteorites: 1980-1990* (National Academy of Sciences, Washington, D.C.)



The Inner Planets

There are five planetary objects in the inner solar system: Mercury, Venus, Earth, the Moon, and Mars. Each of these bodies offers a large and important set of scientific challenges and opportunities—more than will be accommodated within any foreseeable level of resources available to the planetary exploration program. This situation is amplified because of the detail with which we already have scrutinized the Moon and Mars. A wealth of important scientific problems now confronts us as a consequence of the unexpected discoveries and new perceptions that rewarded our early investigations.

In order to facilitate a long-term program with a coherent and consistent purpose, COMPLEX recommended that the major focus of inner planet investigations be on the triad of planets, Venus, Earth, and Mars. These terrestrial planets, generally similar in size, location, and composition, have followed different evolutionary tracks to the present day. Discovery of the reasons for these diverse evolutions, comprehension of the physical phenomena that determine the global structure and behavior of the terrestrial planets and the courses of their evolution, and discovery of the role that life itself plays in shaping planetary evolution, would constitute a profound advance in human knowledge. The juxtaposition of the three similar, yet different, objects provides a special opportunity to attack these scientific problems. The identification of reasons for differences and similarities would provide the basis for a series of important scientific investigations.

ORIGINAL PAGE
COLOR P

VENUS

In examining the progress on inner solar system investigations, COMPLEX was impressed by the important contribution that global maps of planetary surface topography and morphology make to our understanding of planetary behavior and evolution. The major gap in such data for inner solar system objects was the absence of such a map of Venus. ***Consequently, COMPLEX recommended acquisition of a kilometer-resolution surface map as the highest priority objective in continuing investigations of Venus.*** COMPLEX went on to recommend that continuing investigations of Venus include (in order of decreasing priority): 1) ***determining the major chemical and mineralogical composition of the surface material;*** 2) ***determining the composition and concentrations of the various photochemically active gases in the 65-135 km altitude region of the Venusian atmosphere;*** and 3) ***investigating the physical and chemical interactions of the surface with the atmosphere and the composition and formation of atmospheric aerosols.***

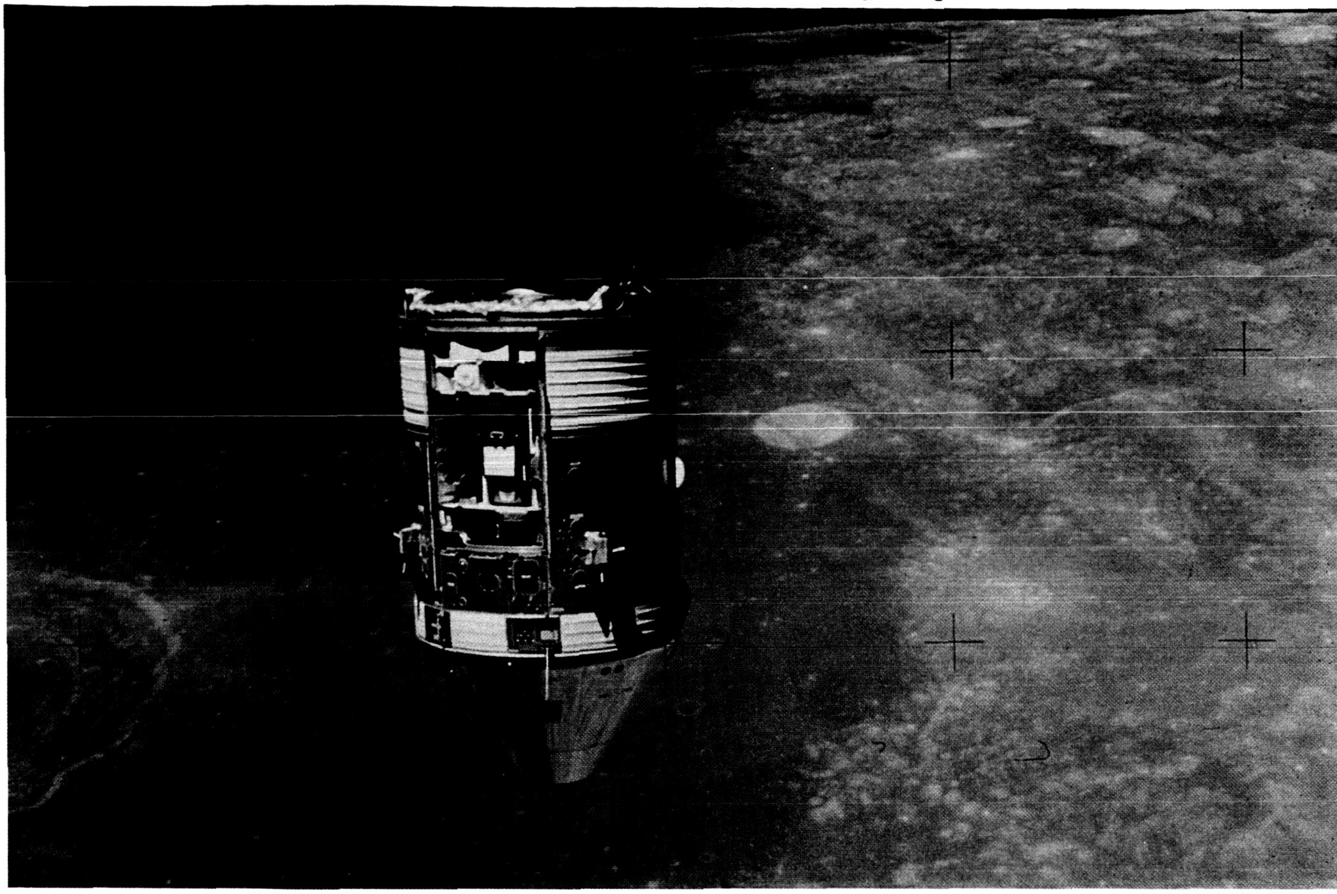
Some important investigations of Venus were relegated to a secondary status because of the lack of immediately foreseeable prospects for their realization. Notably, the acquisition of global seismic data seems to require operation of a long-lived instrument in the hot, hostile environment on the Venusian surface. COMPLEX recommended that consideration be given over the long term to sustained operation of instruments on Venus' surface, both for seismic and other surface investigations. Additionally, COMPLEX recommended preliminary consideration of the return to Earth of a Venus surface sample. Secondary objectives for Venus include exploration of the general circulation of the atmosphere and of the three-dimensional character of Venus' interaction with the solar wind.

MARS

"Mars is a key member of the triad Earth-Venus-Mars and is closely linked to the Earth by virtue of the volcanic, erosional, and climatic phenomena that it is known to exhibit. The study of Mars is essential for our understanding of the evolution of the Earth and the inner solar system." On this basis, two precepts guided the priority of the objectives recommended for continuing study of Mars: "First is the need to carry out intensive studies of the chemical and isotopic composition and physical states of Martian materials to determine the major surface-forming processes and their time scales and the past and present biological potential of the Martian environment. Second is the need to achieve a broad-based and balanced planetological characterization in order that meaningful comparisons can be drawn between Mars and the other members of the triad Earth-Venus-Mars."

The prioritized scientific objectives for continued exploration of Mars are: 1) the intensive study of local areas to (a) establish the chemical, mineralogical, and petrological character of different components of the surface material; (b) establish the nature and chronology of the major surface forming processes; (c) determine the distribution, abundance, sources, and sinks of volatile material, including an assessment of the

Scientific instruments aboard the Apollo *command modules mapped much of the lunar surface in great detail.*



biological potential of the Martian environment now and during past epochs; (d) establish the interaction of the surface material with the atmosphere and radiation environment; 2) to explore the structure and the general circulation of the Martian atmosphere; 3) to explore the nature and dynamics of Mars' interior; 4) to establish the nature of the Martian magnetic field and the character of the upper atmosphere and its interaction with the solar wind; and 5) to establish the global chemical and physical characteristics of the Martian surface.

MERCURY AND THE MOON

Although Mercury and the Moon are important targets of investigation, they lie outside of the recommended focus for the next phase of inner planet exploration. An important consideration in coming to this judgment for Mercury is the difficulty of reaching that planet because of the demands on vehicle propulsion and the difficulty in carrying out scientific investigations of a planet that close to the Sun.

For Mercury, the primary objectives are to determine the chemical composition of the planet's surface on a global and regional scale, to

determine the structure and state of the planet's interior, and to extend the coverage and improve the resolution of topographic maps. Secondary objectives include further exploration of Mercury's magnetosphere and internal magnetic field, determination of the global heat flow, and the gravity and topography of the planet.

For the Moon, the primary objectives include determining the chemistry of the surface and the surface heat flow on global and regional scales, and establishing the nature of any central metallic core. Secondary objectives include mapping magnetic field anomalies near the lunar surface and determining their relationship to geological structure, measuring the gravity and altitude of the surface to understand isostasy and global crustal asymmetry, and searching for possible volatiles frozen into cold traps near the lunar poles.

The Small Bodies

COMETS

Because of the abundance of highly volatile material in comets, they appear to be among the best preserved remnants of early solar system bodies, and in many respects, most representative of the overall composition of protoplanetary/protosolar nebula material. On the other hand, we are essentially ignorant of the locales of comet formation and their relationship to the other major solar-system objects.

Because of their extended plasma envelopes and their consequent strong interaction with the magnetized, electrically conducting solar wind, comets also provide a potentially important opportunity to investigate cosmic plasma-physical processes. These processes are responsible for many of the spectacular aspects of the appearance of comets as they pass through the inner solar system.

The primary objectives of the early phase of comet exploration are: 1) to determine the composition and physical state of the nucleus (and the ejected gas and dust); 2) to determine the processes that govern the composition and structure of cometary atmospheres; and 3) to investigate the comet's interaction with the solar wind. **COMPLEX** ***also recommended that cometary investigations be carried out over a sufficiently large fraction of a comet's traverse through the inner solar system, and ultimately over a sufficiently diverse population, to allow investigation of a comet's evolution during its active life.***

ASTEROIDS

Like comets, asteroids are thought to retain evidence about early solar system processes—evidence that was not preserved on the larger, planetary objects. Two features of the asteroid population in the Mainbelt strongly influence the scientific strategy recommended for asteroids. First, the Mainbelt asteroids are thought to still reside near their relative positions of formation in the solar system (the transition zone between the rocky, inner planets and the volatile-rich outer

planets.) Also, the distribution of asteroid compositions appears to be related to their distribution in space. Since the regular variation in composition may well reflect radial variations of physical and chemical conditions in the protoplanetary nebula, investigation of a sample of Mainbelt asteroids is expected to provide a powerful probe of nebular structure and conditions, at least for the region of space between Mars and Jupiter. Second, some asteroids show evidence of chemical and thermal alteration in the distant past, thus preserving evidence of events whose record has been destroyed for the larger planets and satellites.

The primary objectives for the initial investigations of asteroids are to determine, for several asteroids carefully selected on the basis of diversity, their: 1) compositions and bulk densities; 2) surface morphologies (and to gather evidence for endogenic and exogenic processes and evidence bearing on the character of precursor parent bodies); and 3) internal properties including states of magnetization.

Asteroids are expected to preserve, in their surface material, records of long-term variations in the space environment, including the solar wind, micrometeoroid, solar-flare particle, and galactic cosmic ray fluxes. A secondary objective of asteroid investigations is to determine these long-term variations.

The Outer Planets

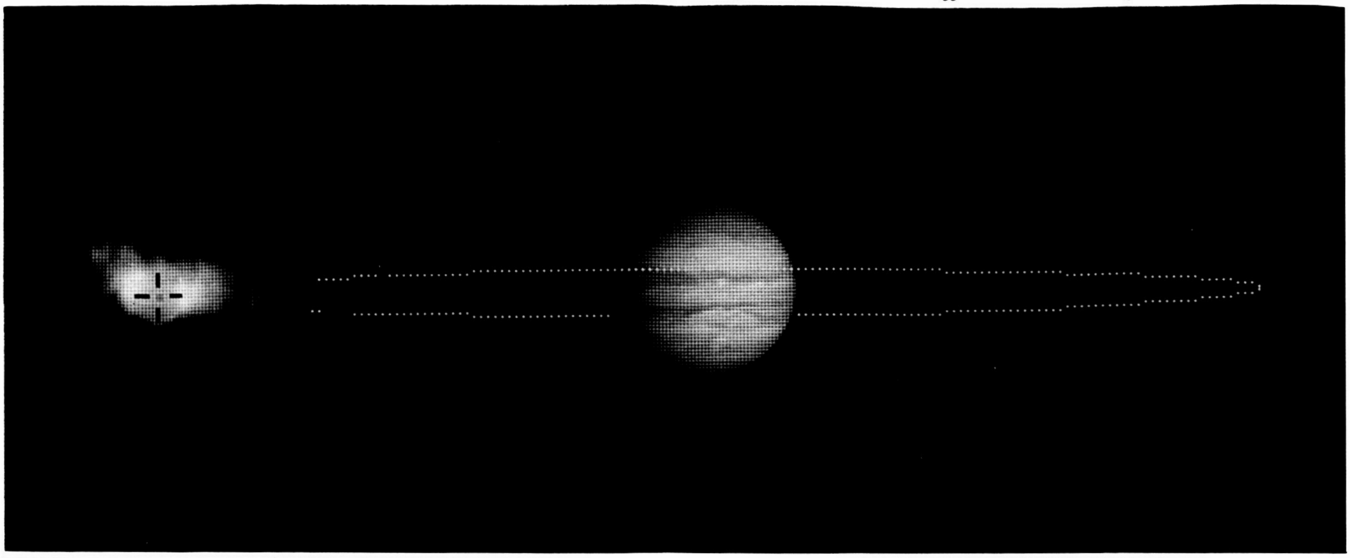
Important investigations of the outer solar system already are underway. The *Voyager* project has accomplished successful reconnaissance of the Jupiter and Saturn systems, satisfying COMPLEX's 1975 recommendations that initial study of these systems be accomplished within the 1970's. Depending upon the continued successful operation of the spacecraft, *Voyager* will carry out the first reconnaissance of Uranus and Neptune during the project's extended phase.

The *Galileo* project, consisting of a planetary probe and an orbiter, will carry out intensive exploration of the Jupiter system. ***The objectives for this next phase of Jupiter exploration are to determine: 1) the chemical composition and physical state of its atmosphere; 2) the chemical composition and physical state of its satellites; and 3) the topology and behavior of the magnetic field and energetic particle fluxes.***

Initial reconnaissance of the outer solar system has revealed a rich variety of unexpected physical phenomena which challenge our comprehension of the way basic physical laws work to shape the behavior of large systems. Eventual explanation of these phenomena will have profound effects on our understanding of the solar system and more distant systems in the universe.

Based on the new information obtained from our first studies of the outer planets, COMPLEX is presently constructing recommended science objectives to guide a continuing outer planets program. COMPLEX already has recommended in its earlier report that NASA be prepared to initiate exploratory preliminary investigations of the Saturn system by the middle 1980's.

The cloud of sodium (left) that surrounds Jupiter's moon, Io, is thought to originate from material off the satellite's surface.



6. Future Directions

Charter of the Committee

Beginning in the mid-1970's, the resources made available for NASA's planetary exploration program began an inexorable decline, exceeding the rates of decline for the space sciences in general and the Agency as a whole (Figure 5). The underlying causes for this decline include the state of the nation's economy coupled with a reordering of priorities at all levels: by successive administrations; by NASA; and by the Agency's (then) Office of Space Sciences. The reasons for the reduced priority of planetary exploration are unclear. It would appear that this reduction is based more on unforeseen programmatic circumstances than on a deliberate policy.

The declining budget of the planetary exploration program, the serious inefficiencies in program execution resulting from the delays in the readiness of a *Shuttle*-compatible planetary upper stage launch vehicle, the lack of an operational equivalent to NASA's *Physics and Astronomy Explorer* program, and the high cost of proposed new planetary missions, have led to a situation in which there have been no new starts in the planetary area for five years. This mission frequency contrasts with the almost yearly rate of missions in the 1970's. Confronted with this situation, the NASA administrator, then Dr. Robert Frosch, organized this *ad hoc* committee reporting to the NASA Advisory Council to study the problem and to recommend to the Agency actions to restore the planetary exploration program to health. The Solar System Exploration Committee was chartered to

> *. . . translate the scientific strategy developed by COMPLEX into a realistic, technically sound sequence of missions consistent with that strategy and with resources expected to be available for solar system exploration. The committee will focus its initial efforts on those missions planned for initiation in FY 84 and then extend its consideration as far into the future as possible, certainly as far as 1995 . . . .*

The composition of the Committee provides representation from the planetary sciences community, the Space Science Board, the aerospace industry, and NASA. During the course of its deliberations, which began late in 1980, the Committee benefited from the views of many other individuals with extensive experience and continuing interest in the planetary program. The involvement of the planetary sciences community was substantially broadened after the first year of the Committee's activity by the constitution of four science working groups, each with the responsibility to recommend mission priorities in its area of expertise and within an implementation framework identified by the Committee.

The main areas upon which the Committee concentrated its activities were: a review of the goals of the planetary exploration program in the light of the overall direction of the Agency; an examination of implementation approaches that could substantially lower the cost of undertaking deep space missions while still maintaining the scientific exploration content of such missions; and the identification of an affordable, Core program of scientific exploration whose implementation would ensure a continued leading role for the U.S. in this arena. The Committee also recognized that an essential element of a healthy program is a well conceived institutional plan that takes into account the contributions that can be made by the NASA Centers, the aerospace industry, and the mostly university-based planetary sciences community. However, the Committee considers that institutional considerations are properly the concern of NASA rather than of the Committee as constituted and, therefore, did not seek to make any specific recommendations on this matter.

The Committee's conclusions are documented in the following sections:

Program Goals

The primary goal of the planetary exploration program has been and remains the scientific exploration of the solar system:

- **To determine the nature of the planets, comets and asteroids toward an understanding of the origin and evolution of the solar system (including the Earth), and toward an understanding of how the appearance of life is related to the chemical history of the solar system.**

NASA is an agency which, since its beginning, has directed most of its resources toward the development of manned spaceflight capability. Given this continuing Agency priority, the Committee concluded that it would be useful to re-examine the goal of the planetary exploration program in the light of NASA's overall, long-range plans. This re-examination was undertaken to determine whether, after two decades, the program goal is still compatible with NASA's major goals and whether a specific program focus, combining scientific enquiry with more tangible benefits, would serve the nation better than the present dedication to scientific exploration.

As a starting point, the Committee sought to identify the main thrust of NASA's long-range policy. Although NASA as a whole has no clearly enunciated program for the next two decades, the recently announced National Space Policy and the near-term planning goals of the Agency have established these priorities:

- The early achievement of operational status for the *Space Shuttle;*
- The exploration of the benefits provided by an operational reusable launch vehicle;
- The establishment of the permanent presence of man in space; and
- The continued pre-eminence of the U.S. in the space sciences, in aeronautics, and in the application of space techniques for the benefit of the nation.

Like all NASA programs, the planetary exploration program will benefit from the lowering of launch costs, one of the major goals of the *Shuttle* development. In contrast to the other space science programs, planetary exploration cannot be undertaken primarily from Earth orbit, and planetary spacecraft can derive no first order benefits from the availability of a reusable launch vehicle as opposed to a conventional vehicle. The establishment of a permanently manned space station in Earth-orbit, however, would be expected to have an important impact on the planetary exploration program. Such a facility might be used as a "jumping-off point" for deep space launches with potential advantages for planetary spacecraft requiring large internal propulsion systems (a space station could be used, in principle, for the final assembly and fueling of such spacecraft). In the longer term, the permanent presence of man in space would most likely lead to requirements for the use of bulk material resources which could be made available from the Moon or from Earth-approaching asteroids in an energetically more efficient manner than by continuing to rely on transporting material from the Earth's surface. Furthermore, the technology developed to sustain a permanent space station in low Earth orbit and to transport men to and from geosynchronous orbit could be adaptable for manned missions to these relatively accessible bodies. Thus, the implications of the development of a space station—itself made possible by an operational *Space Shuttle*—for the future direction of the planetary program clearly need examining.

The last mentioned of the Agency priorities—the maintenance of U.S. pre-eminence in the space sciences and in the use of space techniques—has common implications for all space sciences and is immediately consistent with the recommendations of the Space Science Board which form the basis for the current planetary exploration strategy.

In light of the above considerations, the Committee concludes that a vigorous program of planetary exploration continues to be entirely consistent with the Agency's future direction. Furthermore, the Committee considers that, in time, the expansion of man into space will place significant requirements on the program, especially in terms of providing data and information about the Moon and Earth-approaching asteroids. Eventually, such information also will be

required for Mars, the most Earth-like of all the other planets in the solar system, and a body potentially capable of limited colonization.

Given these considerations, the Committee examined the following three goals as alternative potential focuses for the program:

- To provide a basis for better understanding the Earth through the comparative study of the planets;
- To provide a scientific basis for the future exploitation of near-Earth resources; and
- To provide precursor information required to undertake subsequent manned exploration of Mars.

Members of the Committee were asked to analyze the implications of each of these alternative focuses and to report subsequently to the Committee, where the issues were examined in depth.

The conclusions reached as a result of these studies are as follows:

1. ***The goal of better understanding the Earth by comparison with the other planets should continue to play the important but secondary role that it already occupies in the current strategy for planetary exploration.*** Our growing ability to understand the evolutionary history of the Earth and its geological and atmospheric processes (including the crucial role of life in these areas), has arisen in large part because the growing base of data about the other solar system bodies has allowed us to develop a new, planetary-scale perspective of the Earth. The Committee expects that a balanced scientific approach to the exploration of the solar system will continue to be optimal for adding to our understanding of Earth since so much of that understanding is based on the synthesis of data from many disciplines. ***Therefore, no new strategic approach or changes in the focus of the program to this end are proposed at this time.***

2. ***The planetary exploration program should have as a new secondary goal the provision of a scientific basis for the future utilization of resources available in near-Earth space.*** The concept that lunar and asteroidal materials will eventually prove to be economically important appears most plausible. The time at which these resources might actually be exploited depends both on the rate of advance of manned activities in Earth orbit and on the Moon, and on the state of our knowledge about the availability of valuable resources. It is beyond the competence of the SSEC to estimate the first of these two factors; but the Committee concludes that we are ready to undertake an initial systematic survey of lunar and asteroidal resources using already developed techniques. Given the long lead-time required to move forward on economic ventures, the Committee considers that it is none too early to begin a scientific survey of these resources. ***The recommended mission strategy, therefore, should explicitly include missions that, together with suitable ground-based and Earth-orbital techniques, are capable of acquiring data characterizing the chemical, mineralogical, and physical properties of the Moon and the Earth-approaching asteroids to a level sufficient to provide a first order assay of these bodies.***

3. ***The adoption of a program focusing on Mars cannot be justified at present.*** Given the limited resources expected to be available in the next several years, such a focus would require a de-emphasis of other essential elements of the program. Since the exploration of the small bodies and of the outermost planets has not even reached the reconnaissance stage, any emphasis on a single planet would inevitably jeopardize the basic scientific goals of solar system exploration which call for balanced progress. A Mars focus could only be justified if manned exploration were contemplated. At present no such plan exists, even in the Agency's projections for the future. ***Mars should retain its place as one of the most scientifically significant planets for future intensive study, but not to the exclusion of other targets.***

In summary, the Committee concludes that ***the fundamental motivation for the planetary program remains the broadly based exploration of our solar system that has produced a multitude of major discoveries during the last two decades.*** Beyond intrinsic exploratory rewards, this program continues to produce a rich harvest of scientific information with which we study the origin and evolution of the solar system and the delicate balance that produced and maintains life on Earth. The exciting discovery phase is far from complete. In some senses it is just beginning: the comets and asteroids, the outermost planets and even the surface of Venus are unexplored. In other areas, where an exciting beginning has already been made, the potential value of carrying out exploration to the level of more detailed study promises to be of the greatest scientific significance because our understanding is still so rudimentary.

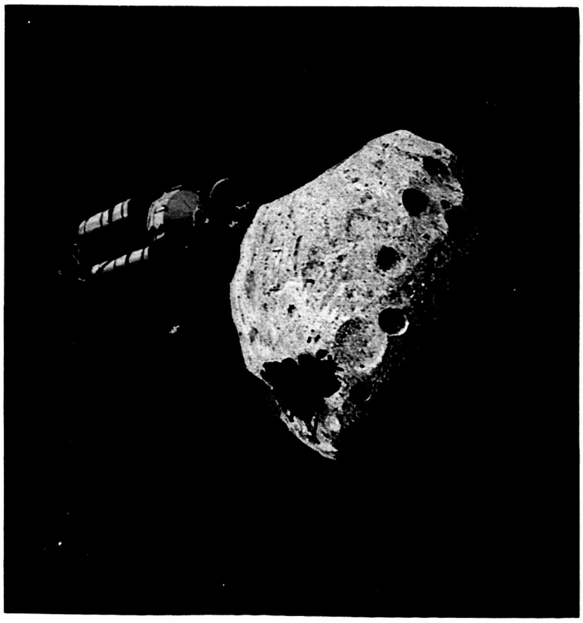
The Committee also recognizes that ***a secondary motivation for planetary exploration is the direct pursuit of practical benefits for the future.*** Comparative planetological studies directed toward a better understanding of the origin and evolution of the Earth, and also of the major geological and atmospheric processes at work on Earth, have already provided us with insights that could be acquired in no other way. We have recently witnessed the rapid re-emergence of the U.S. manned space program with the advent of a first generation re-usable launch vehicle—the *Space Shuttle*. There are no obvious technological impediments to the eventual development of large scale economic enterprises in near-Earth space. Although such developments may not even begin in this century, it is timely to assess the potential of mineral and volatile resources in that region of space, specifically on the Moon and the Earth-approaching asteroids.

Extraterrestrial Resources

The list of resources available for use in space includes unlimited solar energy, a full range of raw materials, and an environment that is both special and predictable. Over the past two decades, investigations of the Moon, meteorites, and asteroids have provided clues about the rich source of minerals and other elements that can be mined using this abundant energy and special environment.

For example, the *Apollo* missions determined that the average lunar soil contains more than 90 percent of the materials required to build a complex industrial installation. The highlands dirt is rich in anorthosite, which is suitable for the extraction of aluminum, silicon, and oxygen. Other lunar soils are known to contain ore-bearing granules of ferrous metals like iron, nickel, titanium, and chromium. The iron can be concentrated from the lunar regolith (soil) prior to refining simply by sweeping magnets over it to gather the iron granules scattered within.

There is some reason to believe that water ice and other frozen gases may be locked into the lunar surface in the permanently shaded polar regions. Should this be the case, "ice mines" could provide the oxygen and hydrogen—using solar electrolysis—necessary to support and fuel future lunar bases.



Reconnaissance of an Earth-approaching asteroid

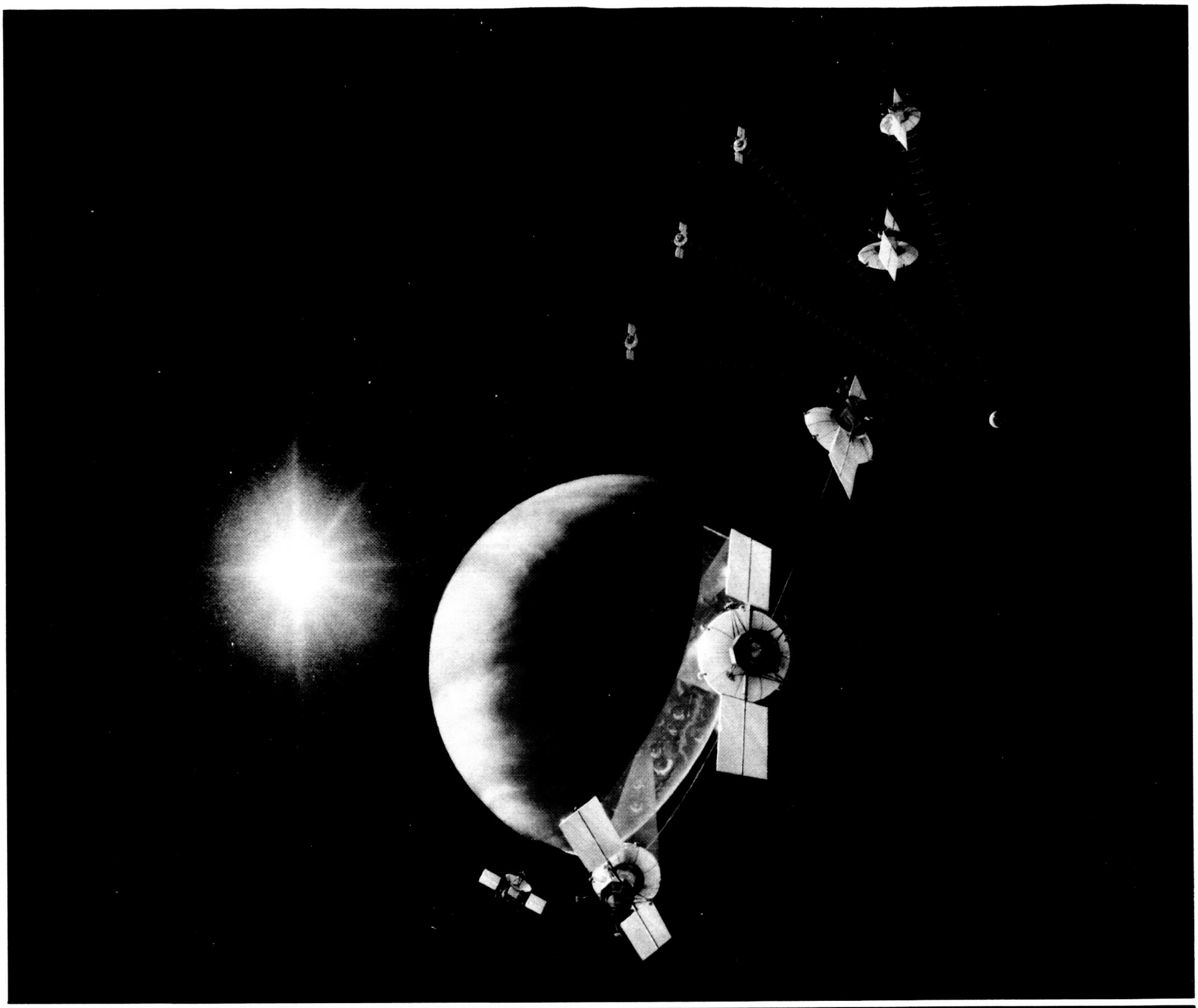
Earth-based spectroscopic evidence and analysis of meteorites, which are thought to be spawned by the asteroids, suggest the following:

- C-class (carbonaceous) asteroids, similar to the famous Allende meteorite, contain up to 10 percent water, six percent carbon, significant amounts of sulfur, and useful amounts of nitrogen;
- S-class asteroids, more common near the inner edge of the Mainbelt, and among the Earth-approaching asteroids, may contain up to 30 percent free metals (alloys of iron, nickel, and cobalt, along with high concentrations of precious metals);
- E-class asteroids may be rich sources of titanium, manganese, magnesium, and other metals; and
- Chondritic asteroids are thought not to have undergone geochemical differentiation and therefore not to have hidden their metals in inaccessible cores.

The latter class may be most valuable of all, particularly since they are among the much more accessible, Earth-crossing population. The upper layers of such chondritic asteroids would be a more concentrated source of metals, such as nickel, than the richest known deposits on Earth.

Metal extraction probably could be quite easy, using the standard carbonyl process, which is the same method employed at the famous Sudbury, Ontario facility to purify most of the world's supply of nickel. Simple clamshell mining probably would suffice to gather the ore. Carbon monoxide gas would be passed over the ore, at relatively low pressure and temperature. Iron and nickel in the ore would combine with the gas to form the volatile, carbonyl liquid which can be easily decomposed into the pure metals. A magnetic, metallic residue of cobalt, which also contains all the precious metals like silver and gold, could be filtered out or electrostatically precipitated. (Although the economics of asteroid mining are very uncertain, it is of note that a kilogram of these cobalt solutes is worth approximately $10,000.) The entire refining process uses relatively little power, passive thermal control, and few moving parts. The necessary carbon monoxide could be obtained by heating the asteroidal soil and could be recycled. The only catalyst known to accelerate this process is sulfur, which is thought to be abundant in asteroids (as it is in meteorites). The process thus appears ideally suited for remote operation.

Late this decade, the entire surface of Venus will be mapped to a resolution of one km by the Venus Radar Mapper, *a Core mission.*



7. Core Program Implementation

The operation of complex scientific spacecraft in deep space presents technological challenges beyond those routinely encountered in Earth orbit. Such challenges, which inevitably add to mission costs, have in the past been viewed as an attractive feature of the planetary program because of their stimulus to technological advance. Now, however, circumstances have changed and cost considerations have assumed paramount importance in the unmanned space program. Thus, we are challenged to define a program that will continue to push back the frontiers of planetary science while constraining costs and providing institutional stability.

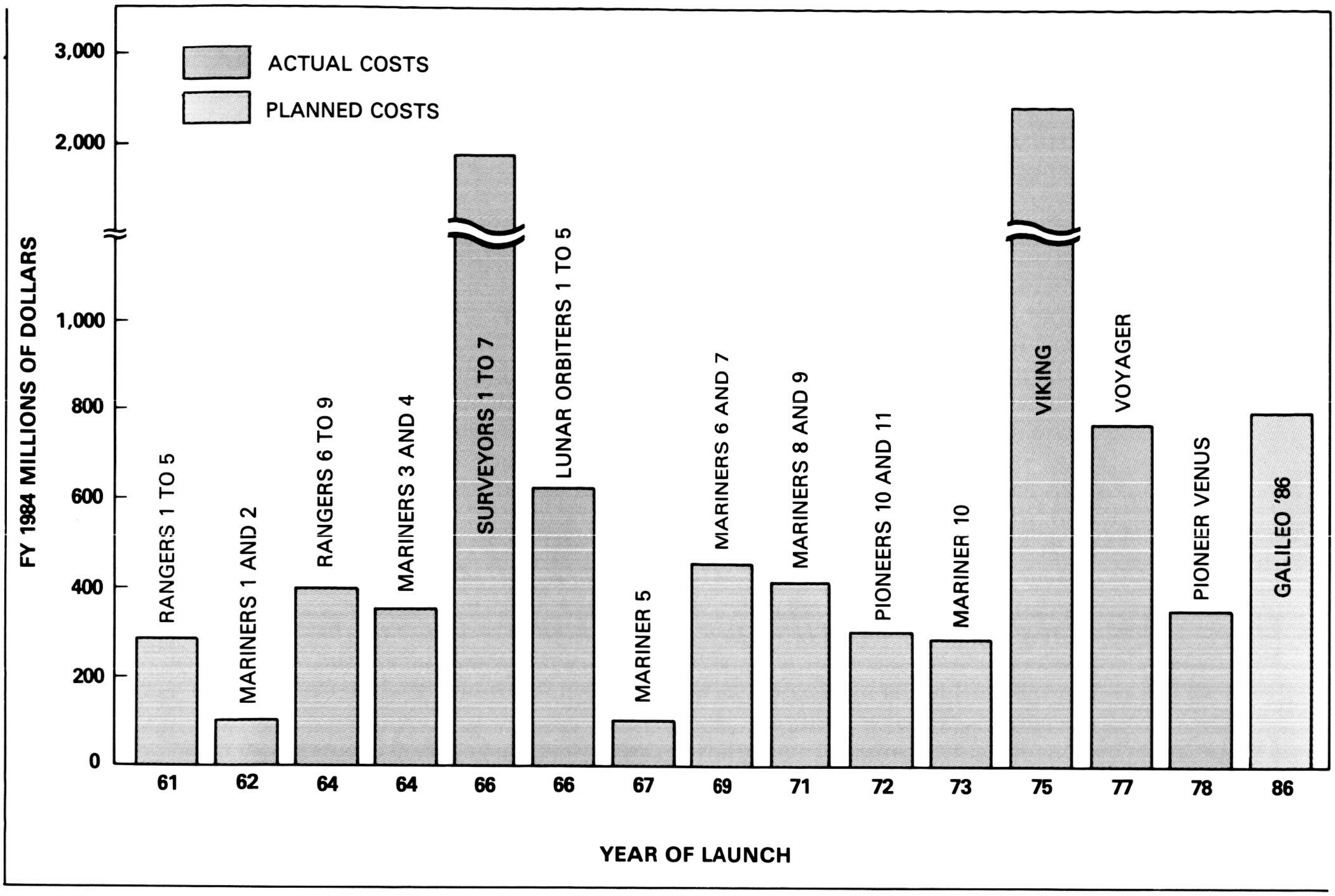


FIGURE 6. **PLANETARY MISSION COSTS**

Contrary to what appears to be a widespread impression, the costs of planetary exploration missions in recent years have increased relatively modestly (Figure 6) given the general inflation, the increased capability of second generation missions, and the long trip times of missions like *Voyager*. Nevertheless, the absolute cost of planetary missions ***is*** of great concern: in view of the high quality (as evidenced by the Space Science Board endorsement) of the planetary missions that have been proposed in recent years but have not received approval, it is clear that cost considerations have been a dominant factor in dictating the lack of acceptance of these initiatives. Therefore, the Committee has concluded that a reduction in the cost of most planetary exploration missions is essential if the program is to regain its vigor. The SSEC focused much of its effort on achieving cost savings while maintaining scientific excellence.

A first step was to identify the key factors that drive mission costs. There are three primary factors: the degree of hardware and software design inheritance from mission to mission (including ground operations); the scientific scope, and hence complexity, of any given mission; and the degree of change after the mission is approved.

Institutional considerations, including the need to maintain national planetary exploration capability at the NASA field centers at a time of low program activity, have also contributed.

The first two factors appear to be reinforcing. As the time between missions increases beyond a certain point, inheritance falls off substantially, while at the same time there is a strong tendency to maximize the scope of new candidate missions to compensate for the infrequency of starts. Thus, costs accelerate and the prospect for political approval of new missions diminishes. Examples of broadly-scoped, custom-designed new mission concepts proposed in recent years include a *Mars Rover*, the *Venus Orbiting Imaging Radar* mission, a *SEPS*-powered* *Comet Flyby/Rendezvous* and a *Saturn Orbiter/Dual Probe*. Typically these missions would have cost between a half billion dollars and one billion dollars—more than the market could bear even though each mission was fundamentally well conceived and would have made a large scientific contribution. ***The Committee concludes, therefore, that it must limit its near-term recommendations to missions that are restrained and focused in scope and where high inheritance can be achieved.*** Such missions will make up a ***Core program*** that should be augmented by technologically challenging missions only when the current fiscal constraints can be relaxed.

Inevitably, some of the highest priority science goals recommended by the Space Science Board cannot be accomodated within the Core program. Specifically, the return of samples from Mars and the exploration of the Martian surface by mobile laboratories are goals whose scope inevitably must lead to costs that are unaffordable given current NASA priorities. Furthermore, combining as many objectives as are technically feasible into a single mission to lower the total cost of achieving all the objectives can provide a cost-effective mission that is not affordable. Some judicious combination of objectives may indeed provide overall cost benefits. For example, geoscience and climatological goals that can be pursued from Mars orbit call for similar mission characteristics and instrumentation, and therefore are obvious candidates for joining in one mission. In most cases, however, it is expected that mission costs will prove unaffordable if the combining of disparate objectives is attempted. For example, a *Mars Aeronomy Orbiter* mission might be combined with a surface network mission where the orbiter would serve as both probe carrier and telemetry relay. While attractive in principle, the total cost falls outside the range of acceptability at this time. Therefore, such a case calls for the separation of mission objectives.

Once approved, the missions in the Core program must be insulated as far as possible from change since the costliness of redirection is almost always disproportionate to the magnitude of the change in question, as experience has amply demonstrated. Some of the changes incurred by planetary projects in the past were outside the control of planetary program management (most notably the delays and redirection of the *Galileo* mission that arose from the repeated launch vehicle program changes) while other, smaller changes have been the direct responsibility of planetary program management (for example, where experiment scope has been at issue.) Regardless of origin and

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* SEPS: Solar Electric Propulsion System—a low thrust, ultra-high efficiency system that uses ion thrusters and is powered by solar panels.

immediate responsibility, the redirection of projects and the solving of unanticipated technical problems impose severe cost burdens.

To maintain the tightest possible control over costs, the missions of the Core program ***should impose no requirements for enabling technologies*** (for example, new upper stages, low-thrust propulsion systems, mobile lander systems, intact sample return capability). In addition, Core program missions ***must be subject to highly disciplined management.*** Specifically, the recommendations contained in the Hearth Report should be followed.

Institutional issues that influence the cost of planetary missions did not receive in-depth examination by the Committee. Nevertheless, the Committee considers that institutional considerations may be as important as technical issues. The Committee recommends that ***NASA develop a plan, responsive to the requirements of the Core program, for the optimum deployment of institutional resources.***

Implementation Implications

From the outset of its deliberations, the SSEC has recognized that achievement of all the scientific objectives set out by the Space Science Board for planetary exploration would call for a costly program of great diversity—one that would require the whole range of automated exploration techniques: remote sensing orbiters, atmospheric entry probes, surface landers, mobile laboratories, and sample return spacecraft. Much of the cost would be involved in the development of challenging new technologies to permit automated surface mobility and the return of selected samples. The Committee noted that, if these two, large-scale undertakings are excluded from a Core planetary exploration strategy, and if the remaining scientific objectives are divided into bite-sized pieces, then a program could be formulated that is technologically much less ambitious, well within the boundaries imposed by available launch capability (the *Space Shuttle* together with the two-stage *IUS* or the *Centaur*), and which uses technologies that have already been successfully demonstrated in the program. ***With such an approach a high level of science return could be achieved at modest cost.***

In this Core program, normal instrumentation advances would certainly be looked for but no formidable challenges have been identified. On this basis, the problem of formulating an optimum mission strategy can be reduced in large part to: 1) the question of how to implement missions of a well understood character most cost-effectively; and 2) the identification of the priorities among these missions. The Committee's suggested mission implementation approaches are discussed below. The identification of mission priorities forms a separate section.

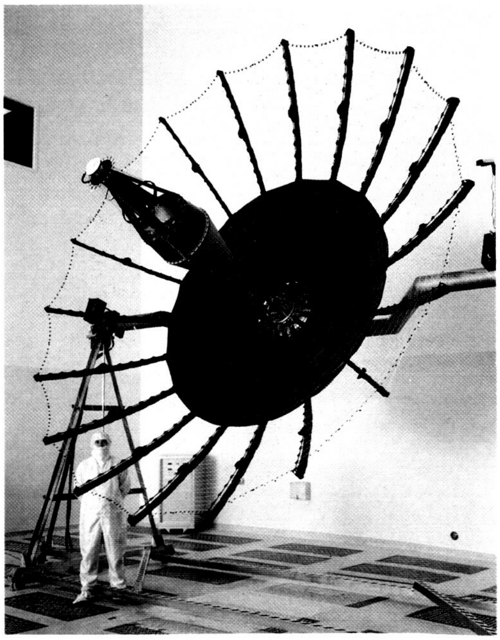
Implementation Approaches

Three different approaches have been developed to provide NASA with the means of carrying out planetary exploration missions at minimum cost and with high scientific return. These approaches are:

1) the use of existing spare hardware, and hardware duplicating that in production for the **Galileo** *mission.*

Although it is clear that existing spare hardware is available only in limited quantity, there are some real, immediate advantages to be gained by making use of such spare subsystems. The *Venus Radar Mapper (VRM)* mission is an important case in point. In discussions with NASA representatives, the Committee was assured that the cancellation of the *Venus Orbiting Imaging Radar (VOIR)* mission in February 1982 was based on considerations of cost alone. A new mission approach—*VRM*—was conceived to address the principal goals of *VOIR* while reducing costs substantially. The *VRM* approach depends on recent advances in processing radar data, maximum use of existing spare hardware to construct the radar-carrying spacecraft, and a reduction in science objectives.

The *VOIR* imaging radar needed a low circular orbit and a complicated communications system. New technology developments allow the processing of imaging radar data from an elliptical orbit; by moving to such an orbit, the costly implications of aerobraking (planned for *VOIR*) have been eliminated. By eliminating the high resolution imaging capability of *VOIR* (0.1 km maximum) but maintaining nearly global coverage at the lower resolution specified by COMPLEX (better than 1 km), and by telemetering the data to Earth from the apoapsis part of the orbit using the radar antenna, a simpler



Galileo's ***4.8-meter-diameter antenna, made of gold-plated molybdenum wire mesh, will transmit and receive signals from Earth as the spacecraft conducts its 20-month-long orbital encounter with Jupiter in 1988.***

Several components from existing spacecraft will be used aboard the **Venus Radar Mapper** ***as a way of helping to reduce mission costs.***

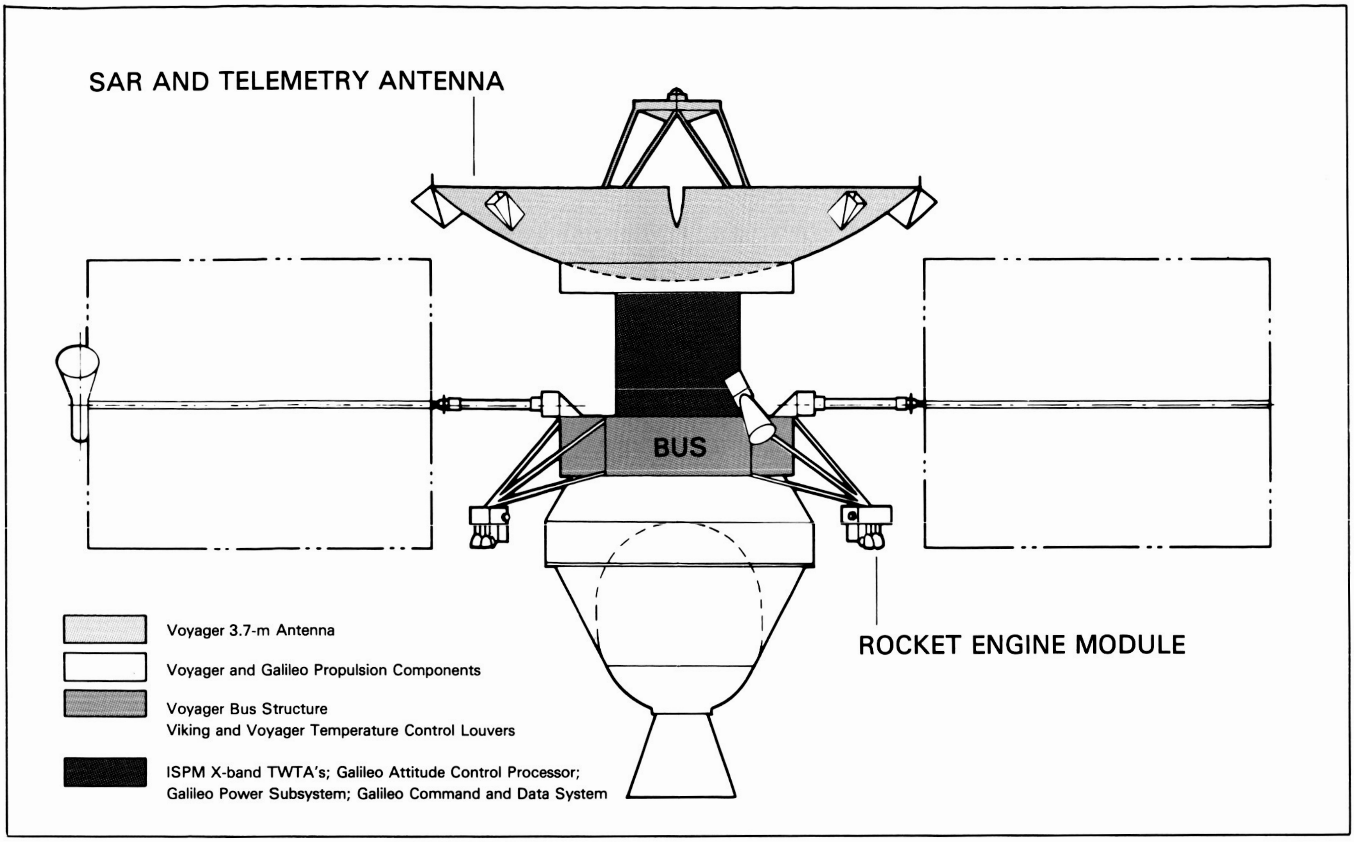


FIGURE 7. ***VENUS RADAR MAPPER***

radar and spacecraft can be used. A major science loss—the removal of the atmospheric remote sensing and aeronomy instruments which address important but secondary science objectives—has led to further savings. Finally, by using spare hardware from *Viking*, *Voyager*, and *Galileo*, the mission cost for VRM has been reduced to less than half that of *VOIR* (Figure 7). The *VRM* mission, which at modest cost maintains the capability to address the first order science objectives, has thereby become a mission of exceptional merit.

When the inventory of existing spare parts has been depleted there will still be opportunities to take advantage of the investment made in the *Galileo* program. In particular, the *Galileo* probe has been designed for the extremely difficult task of entering the atmosphere of Jupiter. *In situ* measurements at Saturn, Titan, Uranus and Neptune would all be less demanding in terms of atmospheric entry. Therefore, if continuity can be achieved with the ongoing *Galileo* project, *Galileo* probe inheritance could play a major role in reducing the cost of using entry probes in outer planet exploration. The required instrumentation would have to be re-examined for each target. Similar inheritance from the *Galileo* orbiter for outer planets and small bodies missions has been examined much less thoroughly than probe inheritance. Generally speaking, such inheritance appears feasible with some limitations imposed by the substantial weight of the orbiter spacecraft.

2) ***the modification of "production-line" spacecraft developed by aerospace companies for a variety of scientific and commercial applications in Earth orbit.***

The aerospace industry now has numerous companies experienced at building highly capable spacecraft for commercial and scientific use in Earth orbit. Although there are few true production lines, the production rates of spacecraft and the competitiveness within this industry are such that the costs of high capability Earth-orbiters are modest by comparison to the specialized spacecraft generally used for planetary exploration. Although it is recognized that no Earth orbital spacecraft is available to be launched into deep space without modification, the potential economies of using "customized" Earth-orbiters for certain planetary missions has led the Committee to examine this possibility closely.

Several specific contracted studies by aerospace companies, the analysis of teams at JPL and ARC, and the critical review of an SSEC subcommittee,* have all pointed to the same conclusion, namely that it *is* feasible to use derivatives of Earth-orbital spacecraft (Figure 8) for missions carried out in the region of the solar system lying between the orbit of Venus and the inner asteroid belt. Significant changes to "available" spacecraft are required, but these changes have little associated technical risk. Efficiencies accrue because it is possible to take advantage of the following: the aerospace industry's spacecraft production capability (facilities, test equipment, etc.); the systems concept and engineering team that each company has brought together; and the capable subsystems already developed for other purposes. The SSEC's subcommittee has concluded that, to maximize the advantages of this approach: 1) management of the project should be left as far as possible in the hands of the selected contractor (rather than becoming an in-house Center project); 2) science instrumentation should be substantially developed prior to project initiation; 3) adequate performance reserve (power, weight, etc.) should be maintained; and 4) special attention should be paid to a disciplined control of all changes and management of reserves. An important requirement is that design policies be established early for factors that stress the spacecraft design, such as fault tolerance, redundancy, magnetic cleanliness and instrument calibration. It was the judgment of the subcommittee that it should be possible, with proper restraint in science and with strict management discipline, to acquire derivatives of Earth orbiting spacecraft for less than $90M (FY 1984 dollars). The subcommittee concluded that this approach promises significant efficiencies as long as science and spacecraft selection are constrained to yield ample reserves at inception of the project and subsequent changes are avoided.

3) ***the development of a new modular spacecraft free of unnecessary complexity and suitable to adaptation with maximum inheritance for a series of missions beyond the orbit of Mars.***

About half of the highest priority missions studied by the working groups for inclusion in a Core program call for mission operations

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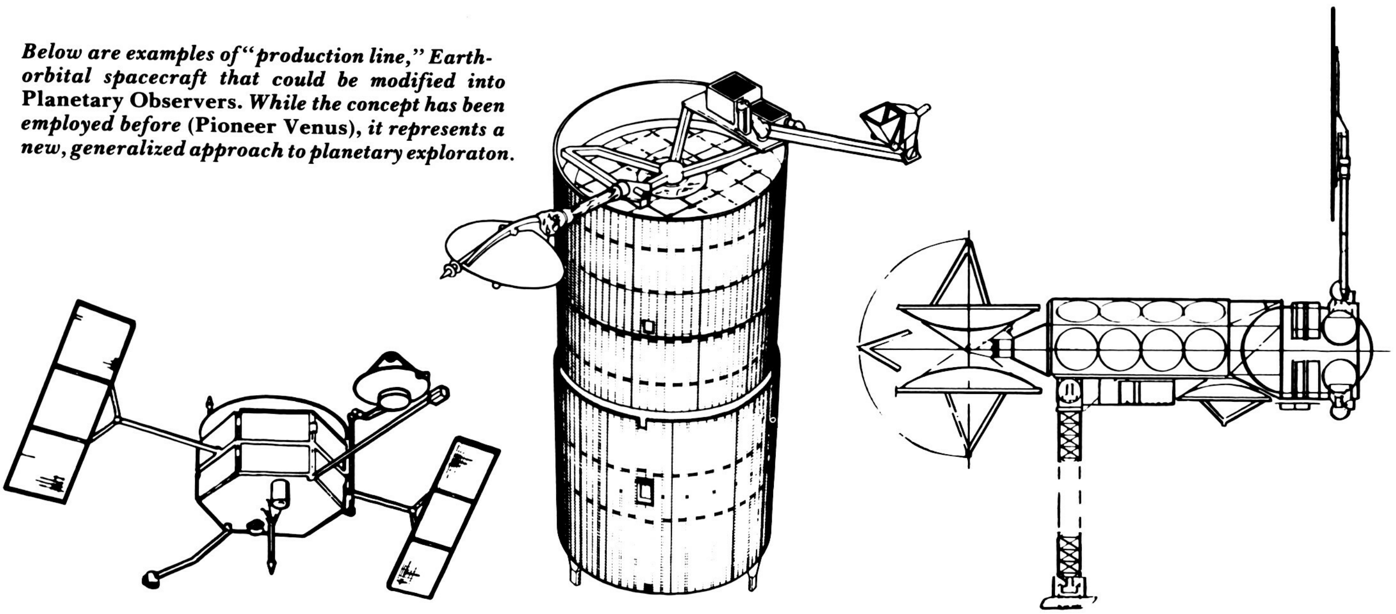
* The Spacecraft Technology Subcommittee was appointed to review critically the validity of the modified Earth-orbiter approach.

A "production line" of Tiros *weather satellites*

Below are examples of "production line," Earth-orbital spacecraft that could be modified into **Planetary Observers.** *While the concept has been employed before* **(Pioneer Venus),** *it represents a new, generalized approach to planetary exploraton.*



TRW FLEETSATCOM DERIVATIVE

HUGHES HS 376 DERIVATIVE

RCA DMSP DERIVATIVE

FIGURE 8. ***PLANETARY OBSERVER*** **CLASS SPACECRAFT**

beyond the orbit of Mars; for example, comet rendezvous, outer planet probes, multiple Mainbelt asteroid flyby and orbiter, and Saturn orbiter. For these missions the modifications to Earth orbital spacecraft needed to provide power, thermal control, communications, etc., are so extensive that the link with production spacecraft is effectively lost. A different approach is required to provide the necessary spacecraft capability. A spacecraft of *Galileo* heritage is one possibility. Another is to consider a new design incorporating heritage from earlier spacecraft where appropriate but also taking advantage of new technology. Given the considerable complexity and weight of the *Galileo* orbiter, the Committee concluded that analysis of the advantages of a new design should be carried out. This new, outer solar system design, informally known as *Mariner Mark II,* is being studied in accord with the following philosophy:

a. The design should be capable of simple reconfiguration to undertake all Core program missions beyond Mars contemplated by the Committee. This requirement led to the concept of a ***modular*** spacecraft with ample design reserves (or "margins") coupled with a multi-mission ground support system.

b. The spacecraft performance (i.e., communications rate, pointing accuracy), should be only that needed to satisfy basic science requirements: technology advances would be used to seek economies rather than to improve performance as has been true in the past. Given the Committee's philosophy that science scope should be constrained to the essentials, the required performance is generally substantially less than that provided by the *Galileo* orbiter.

c. The design, including the ground support system, should aim for simplicity.

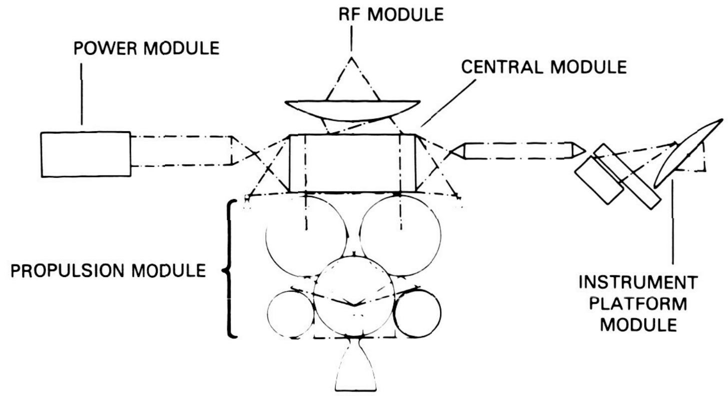
The analysis of *Mariner Mark II* is being carried out by the Jet Propulsion Laboratory. Design concepts draw heavily on earlier planetary missions but also include new technology already under development to be available in the late 1980's and early 1990's. Figure 9 illustrates the modular, reconfigurable design concept. A basic difference between this design and that of the *Galileo* spacecraft is the lack of a spinning section for certain science experiments. This change represents a significant simplification; it also is in line with the philosophy of constraining scientific scope. The central module supports the external modules and houses spacecraft electronics. Basic features of the design are as follows:

The radio-frequency (RF) module includes a fixed high-gain antenna together with its feed and receiver. The antenna size can be changed from mission to mission.

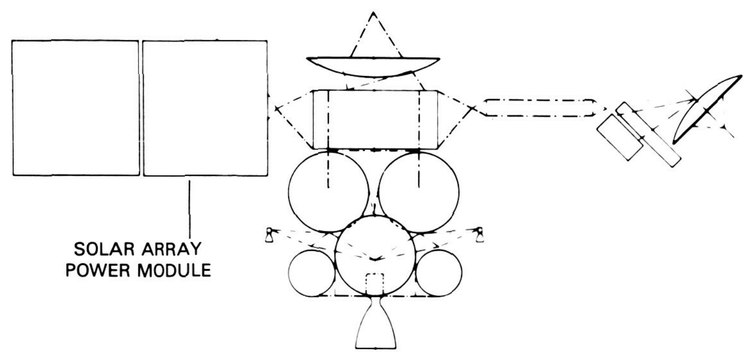
The power module would accomodate either a radioisotope thermoelectric generator (RTG) or a solar panel. An RTG is the power source of choice for outer planet missions, which must operate at great distances from the Sun. However, because an RTG is a source of radioactivity, it cannot be used on spacecraft that carry gamma-ray spectrometers. For such missions, the power source would be a solar panel.

FIGURE 9. *MARINER MARK II* CLASS SPACECRAFT

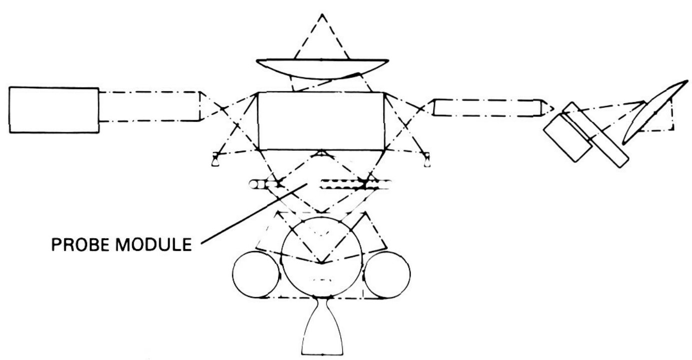
The Mariner Mark II *is designed as a modular spacecraft, the first time a planetary craft has been proposed to serve multiple missions and applications.*



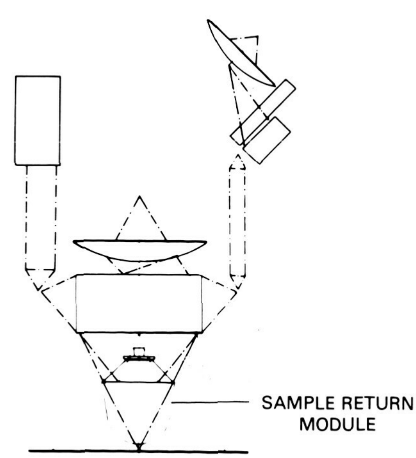
ORBITER SPACECRAFT (A)



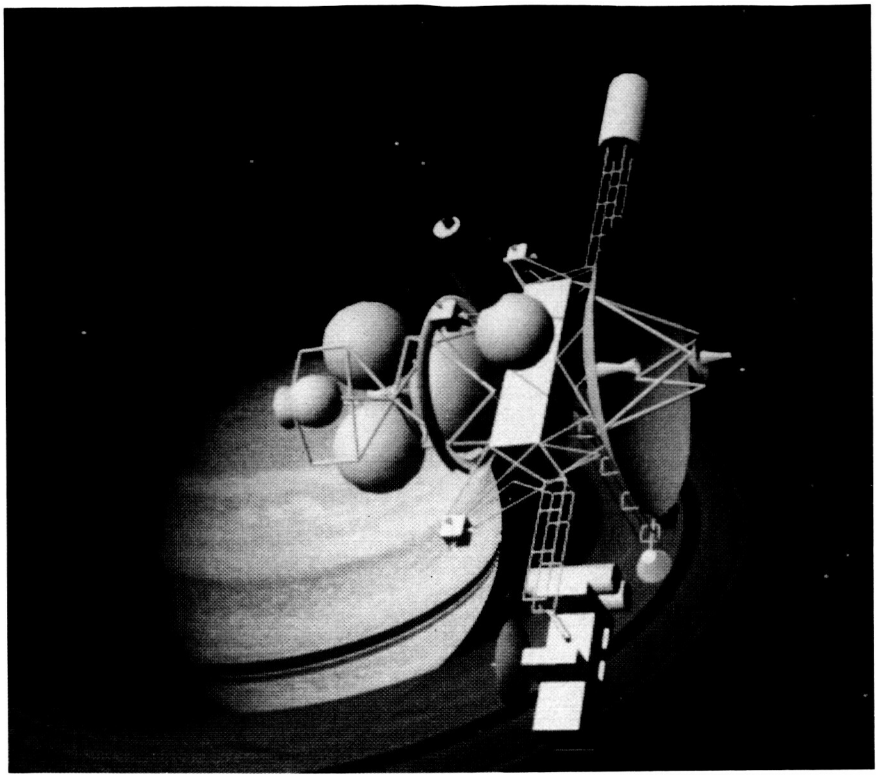
SOLAR ARRAY POWERED SPACECRAFT (B)



FLYBY/PROBE SPACECRAFT (C)



SAMPLE RETURN SPACECRAFT (D)



Core missions to comets, asteroids, and outer plan[...] will be flown using modul[...] versions of this newly designed* Mariner Mark I[...] *spacecraft.

The propulsion module provides both the impulse for trajectory changes (ΔV) and the reaction control required for maintaining the proper orientation of the spacecraft. The spacecraft in Figure 9d has the number of tanks corresponding to a (ΔV) of 2.9 km/sec required for a comet rendezvous.

The scientific instruments and attitude control sensors are located either on the outside of the central module (the "bus"), on fixed booms, or on an articulated platform. This platform can rotate about either of two axes to allow the sensors on it to be pointed in almost any direction to view either reference stars or the target body.

Figure 9 illustrates how the spacecraft could be reconfigured from one mission to the next: Figure 9a is a Saturn orbiter; 9b shows a similar orbiter but with solar power rather than RTG power (comet and asteroid rendezvous spacecraft could be configured as in 9a or 9b depending upon whether they carried gamma-ray spectrometers); 9c shows a *Mariner Mark II* outer planet probe carrier; and 9d illustrates a comet atomized sample return configuration. In the case of the probe carrier the propellant tanks required for interplanetary maneuvers would be jettisoned before the probe is released. The comet atomized sample return spacecraft would be protected during its high speed flight through the cometary coma by a structure serving as both a dust bumper shield and a sample collector. During flyby the power module and the scan platform would be folded back and hidden behind the shield.

The present *Mariner Mark II* concept assumes that NASA will continue to support the timely development of the following new technology:

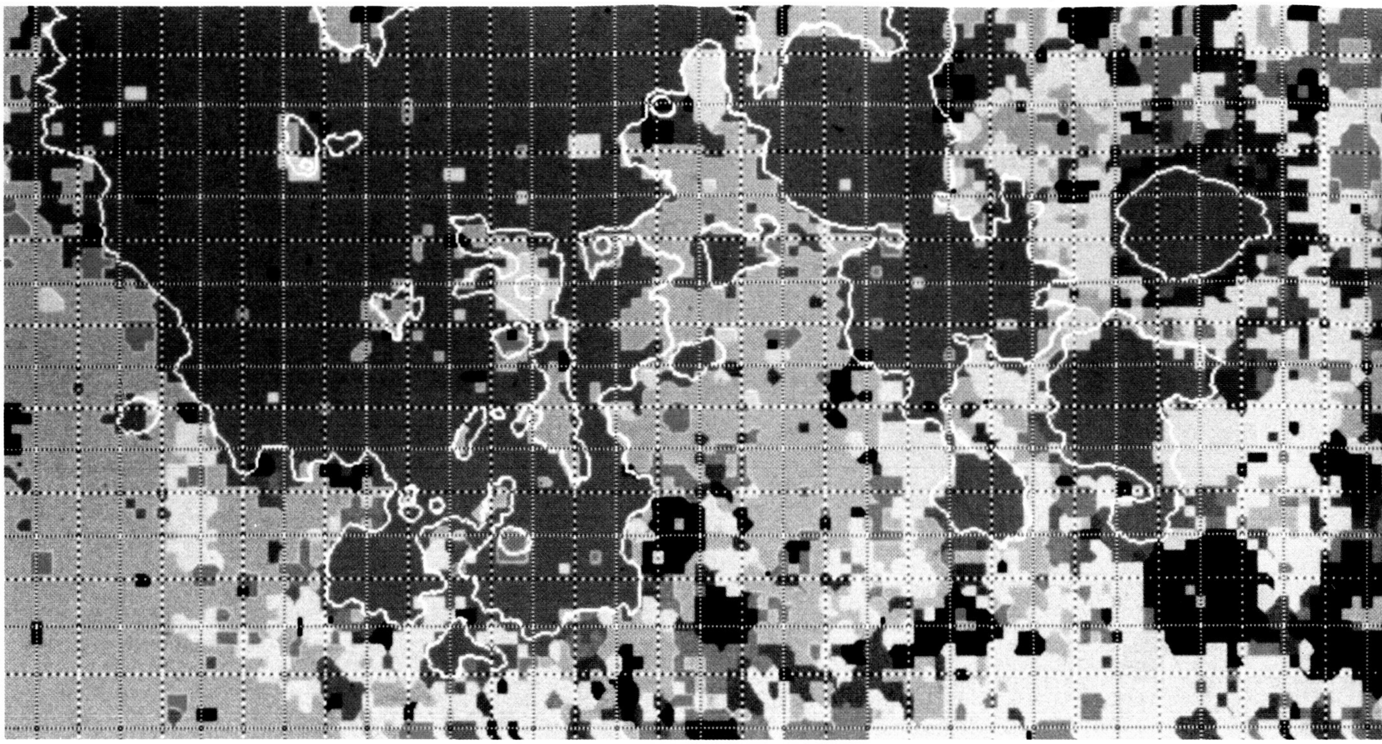
- A communications system that uses X-band frequencies on both the uplink and downlink, and modern solid-state power amplifiers;
- A bus-based data system with bus-interface modules to be placed in each subsystem or instrument to allow flexibility without changes to the data system;
- Fiber-optic rotation sensors (replacing conventional gyroscopes); and
- A CCD-based star tracker that can image a field of stars or can be used in a close-loop mode as a target body tracker.

The basic *Mariner Mark II* spacecraft with reasonable mass margins weighs about 600 kg (compared with about 900 kg for the *Galileo* orbiter) exclusive of the propulsion tanks, fuel and any probes. This total includes 100 kg for scientific instruments. Experience has shown that the estimated mass of a spacecraft inevitably increases during the progression from preliminary to final design to actual construction. Mass reduction programs required by inadequate initial mass margins have been very expensive, and, therefore, the *Mariner Mark II* approach makes a conservative allowance for such growth. But more important than leaving a margin to cover mass uncertainties is the allocation of mass to make interfaces simpler and to reduce cost in other ways. For example, rather than designing new propulsion tanks for each mission (since propulsion requirements vary substantially from mission to mission), the *Mariner Mark II* approach would call for the design, building and testing of only one or two sizes of tanks, filling them only partially for the less demanding missions. For these less demanding missions the spacecraft mass would be greater than if the propulsion tanks were custom built. Such standardization, which calls for ample mass margins, provides worthwhile cost savings.

Another example of how ample reserve can lead to cost savings is in the area of experiment operations. For most planetary missions the limited availability of electrical power, data storage, computational capability, and thermal control requires complex control of the science instruments. Much of the complexity and hence cost (because of the large teams of engineers needed to control the spacecraft) of deep space mission operations arises from these central requirements. The *Mariner Mark II* approach provides sufficient performance reserve to allow most instruments and subsystems to operate at their peak power levels simultaneously, collecting and storing data at maximum rates, thereby eliminating much instrument "sequencing" activity.

An essential program element that allows a philosophy of ample margins to have a major cost saving impact is the availability of a launch vehicle of ample performance: the* Shuttle/Centaur *is such a vehicle and its development will play an important role in making planetary exploration affordable.

This map of the Moon is color-coded according to the age of various lunar features; for example, brown/tan represents oldest regions.



The cost effectiveness of the *Mariner Mark II* approach to deep space exploration depends on several factors: the benefits of improved state-of-the-art technology in many areas; the less demanding requirements levied on the spacecraft, resulting in a simpler spacecraft; the large margins built into the basic design; and the reconfigurability of the spacecraft. The contribution made to the reduction of costs by the last factor will depend on the frequency of new mission starts and the added investment needed to achieve the reconfigurability. The optimum degree of reconfigurability and the needed up-front investment for this aspect of the design will be determined by further analysis. The overall cost benefits provided by the *Mariner Mark II* design philosophy will be valuable independent of this optimization and therefore, the Committee recommends that the *Mariner Mark II* design be carried forward toward an early mission start. The Committee notes that the success of the *Mariner Mark II* approach inevitably will be increased by a high degree of mission activity so that maximum benefits can be achieved through the continuity of engineering teams and the availability of hardware.

Mission Operations

Underlying all three of the mission implementation approaches discussed above is the requirement to provide an up-to-date, multi-mission operations system for operating the spacecraft once they are launched and for processing and distributing the scientific data returned. With the increasing capabilities of spacecraft and experiments, and with the increasing duration of some missions, mission operations represent a substantial fraction of total mission

cost. Thus, the Committee considers mission operations to be a key area for seeking economies. Mission operations cost growth has been compounded by a number of factors, most notably:

- need to develop essentially unique operations and information systems for each planetary mission because each has become, in effect, a singular event;
- antiquation of ground data systems (as distinguished from the spacecraft data systems), characterized by labor-intensive operations and high maintenance costs;
- lack of an adequate end-to-end analysis of the problem associated with the complexities of deep space mission operations and by the handling of large volumes of data from many instruments.

Although the Committee recognizes the importance of developing a multi-mission operations system to replace the current approach, it has yet to examine in detail the progress being made in this area. This task will be undertaken during the final year of the Committee's work. The Committee is impressed that a substantial effort is already underway at the Jet Propulsion Laboratory to define the requirements to be placed on a multi-mission operations system and to develop related new technologies. As a result of this activity, some of the key problem areas are already apparent in broad outline, and some encouraging progress is already visible, so that the Committee has developed confidence that the problem is tractable.

A coherent, long-range mission strategy is an essential element in the development of a multi-mission operations system. Such a strategy is provided by the recommendations of this Committee. Further, the recent report on data management that has been prepared by the Space Science Board's Committee on Data Management and Computation (CODMAC)* identifies many key problems and makes recommendations for solutions. One of the greatest impediments noted by CODMAC is lack of planning and attention to data systems.

The SSEC considers that technical problems do not seem to be the principal obstacles to developing an efficient multi-mission operations system and anticipates that organizational problems will prove most difficult to solve. The development of a multi-mission operations system needs to be accomplished through a focused effort based on clearly defined goals, strategies, and priorities. The organizational responsibilities, both within the Office of Space Science and Applications and within the Jet Propulsion Laboratory, need to be re-examined and re-defined to ensure that this focused effort can take place.

One promising step forward is provided by innovations that permit the automation of spacecraft event sequences; such techniques are already underway at the Jet Propulsion Laboratory. The automated techniques, which rely heavily on advances in computing technology loosely described as "artificial intelligence," have been demonstrated to the Committee. They show clear potential to reduce the labor-intensiveness of planning science data acquisition sequences and controlling deep space vehicles.

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* *Data Management and Computation: Issues and Recommendations*, a report by the Committee on Data Management and Computation of the Space Science Board (National Academy Press, Washington, D.C., 1982).

Lowering Costs—Summary

The Committee believes that the planetary programs have grown in costs because of three dominant factors. The Committee also believes that such costs are controllable and that they can be made affordable even in the current fiscal climate. The Committee's Core program recommendations concerning this, and their implications, are summarized as follows:

1. Maximize hardware and software inheritance

- Use available spare hardware in near term;
  - a. Use for *Venus Radar Mapper.*
- Use Earth-orbital derivative spacecraft for inner solar system exploration;
  - a. Maximize management responsibility of selected contractor;
  - b. Give priority to instrumentation development;
  - c. Provide ample performance margins.
- Develop simple, modular spacecraft *(Mariner Mark II)* for outer solar system exploration, including comets and Mainbelt asteroids;
  - a. Continue the development of key technology improvements;
  - b. Provide ample performance margins.
- Move directly to a multi-mission operations system as rapidly as possible, consistent with the support requirements for ongoing and approved missions;
  - a. End-to-end analysis;
  - b. Immediate commitment and redirection of planning for future mission operations;
  - c. Take advantage of low cost state-of-the-art computer technology;
  - d. Streamline ground data systems;
  - e. Develop optimum organizational structure.

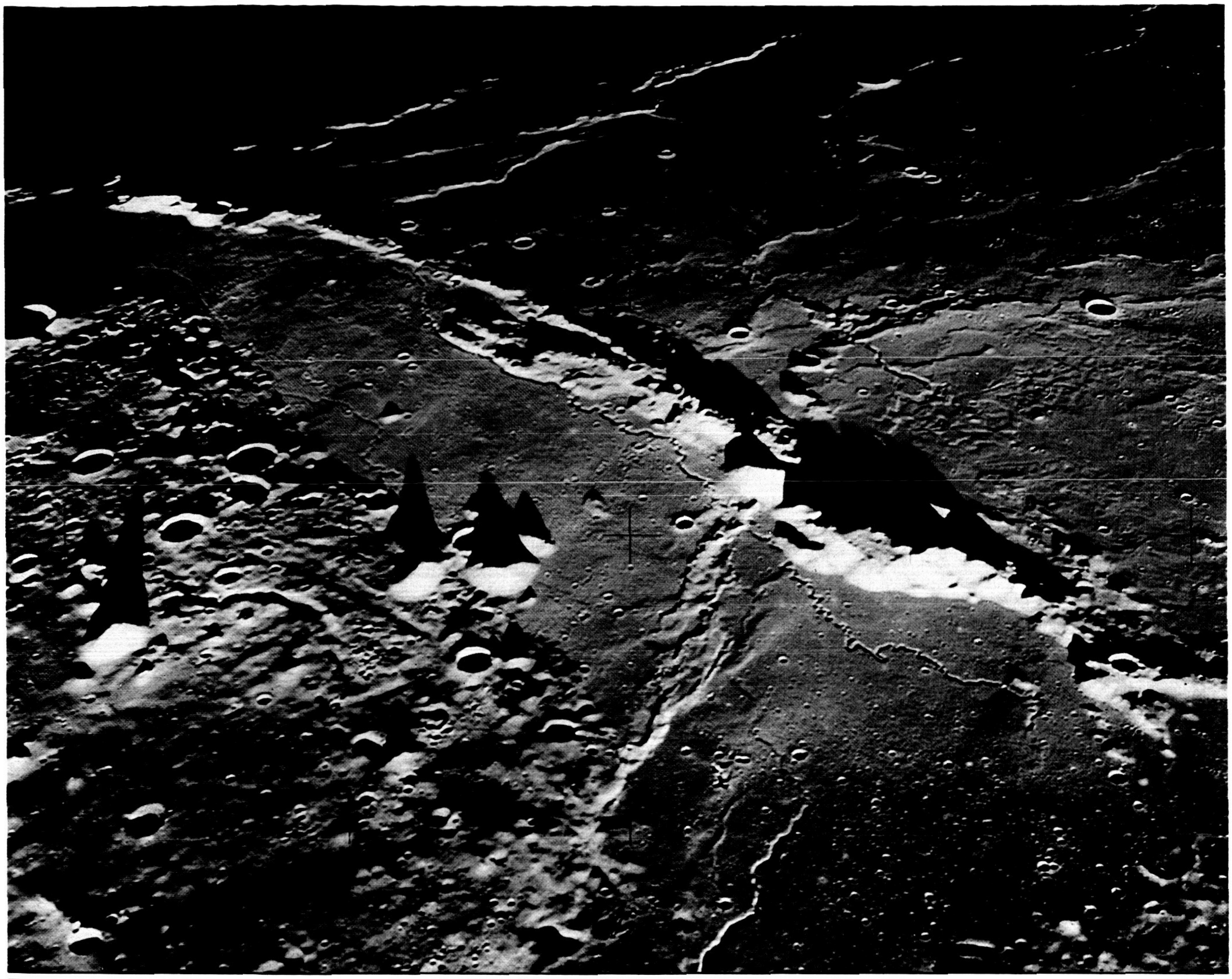
2. Control scientific scope of missions

- Restrain and focus scope of missions;
  - a. Payloads limited to highest priority objectives.
- Judicious separation and combination of mission objectives;
  - a. For example, combine *Mars Geoscience Orbiter* and *Mars Climatology Orbiter* missions;
  - b. For example, undertake separately *Mars Aeronomy Orbiter* and *Mars Probe Network* missions.

3. Minimize changes after original mission definition

- Forego missions where technology developments are of an enabling nature;
  - a. No requirements for launch capability beyond that already available;
  - b. No missions requiring solar electric propulsion system.
- Disciplined Management;
  - a. Follow recommendations of Hearth Committee.

This stark lunar scene of Aristarchus Plateau was photographed from an altitude of 114 km aboard Apollo 15's *command module.*



8. Missions for a Core Program

In arriving at its priorities for a Core program of planetary exploration the Committee relied upon the deliberations of four working groups, each chaired by a member of the Committee and made up of members of the planetary sciences community. These working groups were aware of the science strategies developed by the Space Science Board, the program goals recommended by the Committee, and the implementation approaches that had been identified by the Committee for their cost-effectiveness. Each working group reviewed the scientific progress in the area of its expertise, and, where necessary, provided an update to the COMPLEX recommendations, and examined opportunities for missions. The following summaries draw upon the reports of the four working groups.

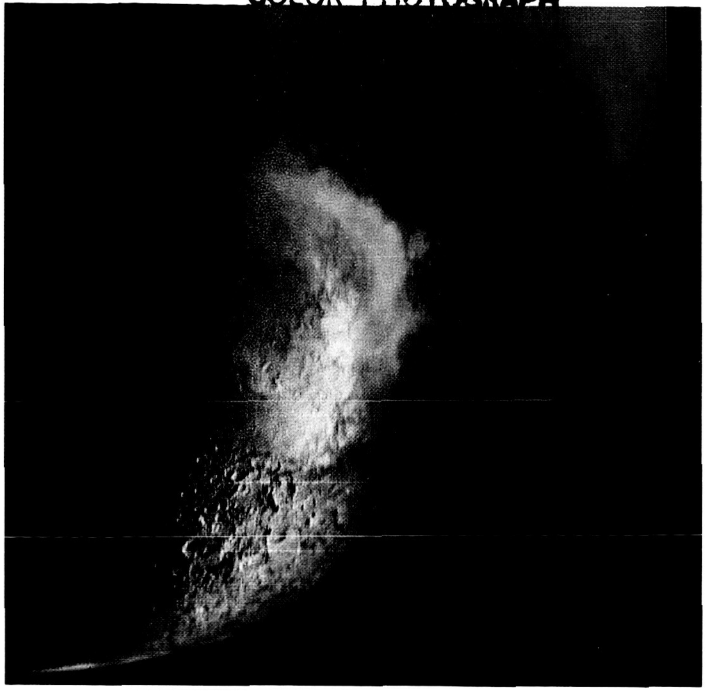
Inner Planets

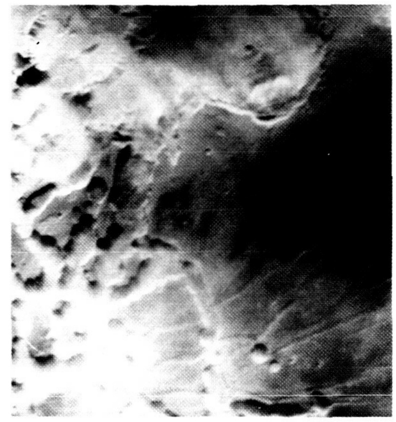
SCIENTIFIC BACKGROUND: The inner planets, composed chiefly of rock and metal, and deficient in volatiles, are smaller and denser than the outer planets. Although similar to each other, they have followed their own unique evolutionary paths. By exploring this diverse family of planets, and by comparing the discoveries with our knowledge of Earth, we seek to determine the nature of the processes involved in the formation and evolution of the inner solar system and the causes of the apparent uniqueness of each rocky planet. We also seek to gain insights into the history, and even into the future, of Earth, and the life that has evolved on this planet.

Because of their proximity, the inner planets have been explored more intensively than the outer planets or small bodies. Missions have included not only flyby and orbiter missions, but also soft-landed spacecraft on Mars and entry vehicles into the Venus atmosphere. We have even sent men to explore the Moon and bring back samples. The Soviet Union has landed a series of complex spacecraft on Venus, has operated mobile laboratories on the Moon and has returned lunar samples using automated techniques.

The repeated *Apollo* landings brought about an enormous leap forward in the scientific understanding of the planets by providing us with selected samples of lunar rocks and soils and a wealth of other information, including seismic and heat flow measurements. These data have helped us to reconstruct portions of the Moon's history during the first billion years after solar system formation. We are now establishing a clear picture of that violent time. The last stages of the continuous meteoritic in-fall are written on the Moon's surface in the form of innumerable craters and are recorded clearly in the complex fragmentation of the returned samples. During its accretionary phase, the Moon may have melted to depths of a few hundred kilometers. The ancient crust developed during this maelstrom, with sections repeatedly fragmented and reincorporated into the evolving magmas until a thickness was established that could withstand the destructive force of the waning bombardment. The study of the Moon tells us more about Earth's early history than we can deduce by studying the oldest rocks on this planet; few ancient rocks survive on the Earth's continuously recycled surface.

Continued study of the *Apollo* samples provides us with many details of the Moon's history. The time-scale of its evolution has been established and several of the first order questions about the Moon have been answered. Equally important, we have accumulated a reservoir of knowledge that provides a basis for interpreting the evolution of other planetary bodies, including the Earth. The Moon recorded a period of intense meteor bombardment that ended about 3.8 billion years ago, a bombardment that produced many of the large lunar basins and presumably impacted all the inner planets at about the same time. This heavy bombardment of the inner solar system has provided a chronological reference marker, accurately measured for the Moon by radioisotope dating techniques, that has been the basis for constructing the geologic history of Mars and Mercury. We expect that it may serve a similar purpose for Venus.





Bright sections of water, ice, snow, and haze cover portions of Mars' Hellas Basin (left) and Noctis Labyrinthus (right), raising intriguing scientific questions that will be addressed by the Core program's **Climatology Orbiter** ***missions.***

All the inner planets, including the Moon, underwent significant early heating, melting, and differentiation; but the evolution of the Moon and Mercury was terminated sooner than the other inner planets because heat was lost more rapidly due to their small size. The Moon has preserved some rocks dating back to an early episode of melting and crustal formation 4.5 billion years ago and apparently has no rocks younger than the period of volcanic flooding of the lunar maria which ended about 3.0 billion years ago. In contrast, the oldest preserved rocks on Earth are about 3.8 billion years old, and most of the Earth's surface—the ocean floor—is less than 0.2 billion years of age. Although we have observed only one half of Mercury, the available data imply a history even more abbreviated than the Moon's. Extensive lava-flooded basins like the lunar maria are absent on the side of Mercury that has been seen, and the issue of how widespread volcanism has been on this small planet is unsolved. Like Earth, Mars and Venus are sufficiently large that they lose internal heat slowly. Their internal heat engines continued to operate over billions of years, manifested at their surface in the form of volcanic constructs and young tectonic features.

The Earth's surface continues to evolve dynamically. Crustal material is continually created at mid-ocean ridges and destroyed beneath the deep-sea trenches, as the plates that make up the Earth's surface move in more or less steady relative motion. The formation of huge mountain belts, the development of chains of volcanoes, and the driving force behind many large earthquakes are linked to these plate motions. Neither the Moon, Mercury, nor Mars shows evidence of global tectonics of such vigor or the wholesale recycling of the surface into the interior. The surfaces of the Moon and Mercury are old and preserve a clear record of early heavy meteor bombardment and of ancient volcanism, and tectonic features associated with that volcanism

or with tidal spindown and global cooling. The surface of Mars also shows a record of heavy meteor bombardment, modified by subsequent wind erosion, but demonstrates an extensive history of younger volcanism and tectonics. The Venusian surface, hidden by permanent clouds, remains an enigma. Limited low-resolution Earth-based radar images and *Pioneer Venus* altimetric data together suggest a surface with both craters and large volcanoes, as on Mars, together with mountain belts as on Earth. The nature of the convective motions that drive plate tectonics on Earth, the importance of such tectonic processes early in Earth's history, the character of the tectonics on other inner planets, and the causes of the major differences in evolutionary style among the inner planets are fundamental unresolved issues. Exploration of Venus' surface by an orbiting imaging radar is essential if we are to make further progress in these matters.

The collective study of the inner planets implies that all have been melted and internally differentiated, leading to a concentric onion-like core, mantle, and crust. The Earth's interior is known from seismic measurements to be layered, a product of global differentiation. At the Earth's center is a metallic core, largely fluid and in convective motion but with a small solid inner core. The core is surrounded by a mantle of ferro-magnesian silicates, mostly solid and in very slow convective motion. At the surface, the mantle is capped by a thin crust of mostly igneous and metamorphic silicate rocks, overlaid by a veneer of sedimentary material. Each of the other inner planets is thought to be similarly layered, but the evidence is limited.

The Earth has a substantial magnetic field of internal origin, evidently produced by the action of a hydromagnetic dynamo sustained by convective motions in the fluid core of the rotating planet. Of the other inner planets, only Mercury has a magnetosphere comparable in character with that of Earth, though much smaller in size. The Moon shows evidence for a complex magnetic history, now recorded in the remnant magnetism of lunar rocks and of the lunar crust, but the origin of this ancient magnetic field is not known. Venus apparently has no internal magnetic field. The existence of a Martian magnetic field is currently a matter of debate; if any field exists, it is small. The wide differences in the nature of planetary magnetic fields are not understood, but may be related in part to rotation rates and nature of the core.

Understanding the characteristics of the magnetic field is not only important for understanding the nature of the planet's internal structure, but is essential if we are to understand the nature of the solar wind's interaction with a planet. The Earth's field extends through a volume of space many times larger than the planetary volume, forming an umbrella that shields the Earth from the flowing interplanetary plasma; in contrast, the solar wind blasts the Moon directly. Comparative studies of the magnetospheres and ionospheres of the inner planets provide a basis to better understand plasma processes—not only in our own magnetosphere but in general—and to understand the processes of atmospheric loss to space.

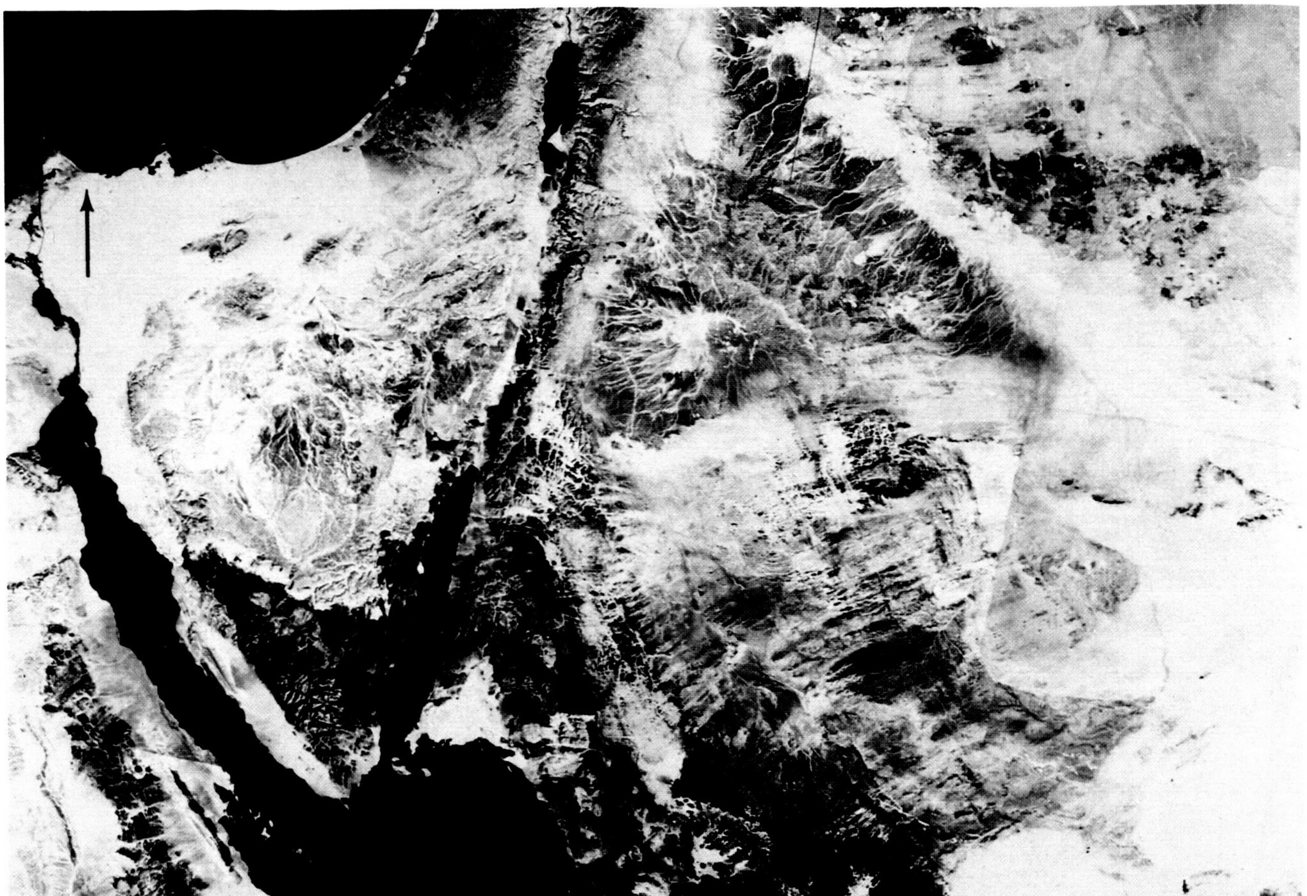
The terrestrial planets vary substantially in the character of their atmospheres. Both Mercury and the Moon are devoid of any stable

atmosphere. The dominantly carbon dioxide-rich atmosphere of Venus is nearly 100 times more massive than Earth's while the carbon dioxide-rich atmosphere of Mars is 100 times less dense than that of Earth. The atmospheres of Earth, Mars, and Venus are all secondary atmospheres, quite unlike the primitive atmospheres of the outer planets. As a consequence of their size, Earth, Mars, and Venus have gravitationally held much of the gas exhaled from their interiors during evolution. The compositions of chemically-inert noble gases found in trace quantities in the atmospheres of these three planets provide fundamental clues about the condensation of inner planets from the solar nebula: the mix of gases in a planet's atmosphere reflects the composition and temperature of the solar nebula from which the planet condensed, the intensity of early outgassing (controlled by the rate and conditions of accretion), the subsequent addition of radiogenic volatiles, such as ^{40}Argon (depending on the thermal history and differentiation of the interior), and atmospheric escape processes, which are commonly mass-selective among isotopes.

Fundamental changes have taken place over the aeons in the atmospheres of Earth, Mars, and Venus. Such long-term evolution can be investigated. The *Viking* entry and lander measurements of variations among nitrogen isotopes in the Martian atmosphere indicate that large quantities of gas have been lost from Mars (the enhanced abundance of the heavier isotopes indicates preferential retention). It is inferred from this and other measurements that Mars has outgassed and subsequently lost to space and to permafrost cold traps the global equivalent of some tens of meters of water. There is additional strong evidence for the earlier presence of liquid water on Mars—which is no longer possible because of the planet's low atmospheric pressure. This evidence is seen in photographic images of giant, dry, Martian channels, evidently cut by running water, and in images of drainage networks. The networks are so complex, in fact, as to suggest the existence of a hydrologic cycle and thus a long, perhaps episodic, history of free water on the Martian surface. On Venus we have measurements of an enhancement of the heavy hydrogen isotope in the atmosphere; this appears to be unambiguously interpreted in terms of the loss of substantial quantities of water. When we acquire high resolution radar images of Venus we may discover evidence of fossil channels and of fossil shorelines that mark the boundaries of former oceans.

At present, Earth is unique among the planets in the large quantities of free water on its surface and in its atmosphere. The dynamics of Earth's oceans play a large, still incompletely understood role in the regulation of the terrestrial climate. Earth is also unique in the large quantities of molecular oxygen in its atmosphere, the result of biological activity. Venus makes a startling contrast: it is covered by a dense global blanket of clouds composed in part of sulfuric acid droplets and has a thick, hot atmosphere of carbon dioxide. Cloud motions and probe measurements indicate a global wind pattern with a substantial dependence on height of the mean wind speed. Surface winds are mild, but gale force winds blow at the cloud tops. Martian winds are variable, as on Earth, with annual episodes of high-velocity winds that give rise to global dust storms. Mars also has marked

This **Landsat** *mosaic of the Red Sea area reveals the geologic movement of the Arabian peninsula northwestwards away from Africa.*



seasons, with a cycle of carbon dioxide between the polar caps providing a major component of atmospheric circulation. Mars shows evidence, in the form of layered sedimentary deposits at the poles, of long-term climatic changes, whose origin is poorly understood. On Earth such climatic changes have given rise to the periodic ice ages.

Earth stands alone among the planets in that its surface, atmosphere, and hydrosphere have provided an environment conducive to the development of life and the evolution of complex living organisms. These life forms have had a substantial influence on the chemistry of the atmosphere and the oceans and on the nature of major sedimentary rock units on Earth's surface. Because the surface of Venus is so hostile (temperatures reach 750°K), Mars had long been thought to be the one other planet with the potential to harbor life; the Viking mission was undertaken to test this idea. The absence of detectable organic molecules and the verification that the intense ultraviolet flux from the Sun reaches the surface suggests that living organisms are not present on Mars now. Whether Mars was less hostile to the development of life during earlier times, when it may have had a denser atmosphere and flowing surface water, is an open question. We cannot exclude the possibility that life originated on Mars, only to die out as the global environment changed.

The history of Earth shares many common threads with the histories of the other inner planets as we now understand them, including early global differentiation of crust and core, outgassing and evolution of an atmosphere, early bombardment of the surface by a heavy flux of meteoroids, and development of a global magnetic field and magnetosphere. However, Earth has many attributes not currently shared with any other known planet, including its oceans, the high abundance of oxygen in its atmosphere, its tectonic plate motions and the consequent complex history of crustal deformation, and its life-forms.

What we are only now beginning to discern is the possibility of a circular linkage between the stable presence of liquid water, the evolution of life, the evolution of the atmosphere, and the global recycling of crustal material through plate tectonic activity. It is this new perspective—still in the chrysalis stage—that promises one of the most profound insights provided by man's exploration of space. It is also this perspective that places emphasis on missions to study Mars and Venus—the terrestrial planets with atmospheres and most like Earth.

DEVELOPMENTS SINCE COMPLEX REPORT: The report entitled "Strategy for Planetary Exploration of the Inner Planets: 1977-1987," prepared by COMPLEX, was issued in 1978. Since that time there have been no fundamental changes in our understanding of Mercury and, although continued studies of lunar samples have led to remarkable knowledge of the details of lunar crustal evolution, the broad framework of lunar history and the scientific objectives for further exploration spelled out in that report remain basically unchanged.

For Mars, our data base has continued to expand for the last five years. The *Viking* orbiters returned increasingly high resolution images until 1980. Until the end of 1982, the *Mutch Station* on the surface of Mars sent back limited data periodically. In-depth data

analysis continues. This extended data base and its continued study have permitted a sharper formulation of some scientific issues, particularly concerning the exchange of volatiles between atmosphere and surface reservoirs and the relationship of these processes to Martian climatology, than was possible at the time the COMPLEX report was written.

The greatest expansion of knowledge about the terrestrial planets over the last five years has been for Venus. The *Pioneer Venus* mission and the Soviet probes, *Veneras 11, 12, 13* and *14,* have produced developments not foreseen in the COMPLEX report, developments that bear significantly on fundamental problems of how the terrestrial planets were formed and subsequently evolved. New Venus data on the abundance of rare gases in the atmosphere are especially provocative because they can be compared directly with the Martian and terrestrial cases. *Viking* measurements revealed that the abundance of Mars atmospheric noble gases is nearly two orders of magnitude less than for the terrestrial atmosphere when normalized to the respective planetary masses. On the other hand, the relative abundance pattern on Mars for the noble gases (except for xenon) was similar to that on Earth and some meteorites. Accordingly, Mars was thought to have accreted with a deficiency of noble gases relative to Earth or to have degassed to a smaller extent than Earth. It was expected that the abundance of volatiles on Venus would closely resemble that of Earth. However, the new data show a very different noble gas abundance pattern on Venus than on Earth, Mars, and most meteorites.

No theory of planetary accretion has yet emerged that convincingly copes with the variations in the volatile inventories of the inner planets. Unfortunately, the atmospheric composition measurements made by various instruments show inconsistencies in their assessments of some important substances, such as krypton, and of the minor, chemically active constituents in the Venus atmosphere such as sulfur compounds, oxygen, hydrogen, carbon monoxide, and water vapor. Better measurements are required to resolve these questions.

In accordance with the overall recommendations of COMPLEX, the Inner Planets Working Group assigned its highest priority to continued investigation of the most Earth-like planets—Mars and Venus, the terrestrial planets with atmospheres. The new goal recommended by the SSEC of assessing the resources available in near-Earth space leads to a high priority to a geoscience study of the Moon, but not of Mercury.

Previous missions have determined many basic properties of the terrestrial bodies—their form and surface features, their density, the general structure and composition of their atmospheres, and the properties of most of their magnetic fields. Many equally basic questions remain, most of which cannot be answered by a single well-defined experiment or even by a set of experiments on a single spacecraft. Questions such as the nature of a planet's interior, the bulk composition of a planet, the history of its surface, or the evolution of a planet's atmosphere are only "answered" by building sets of constraints. Such constraints are based on the integration of measurements made by several different instruments which, in turn, call for different types

of missions. Some questions are best answered by simultaneous measurements from more than one spacecraft; other questions are only answered by the comparison of similar data from several planets.

The major mission modes of interest are remote sensing orbital missions and *in situ* missions of several kinds. Orbiting spacecraft can carry out comprehensive geoscience mapping by remote sensing of the morphological, lithological, and chemical provinces of the planet and can characterize a planet's global properties including topography, gravity, and magnetic fields and atmospheric and ionospheric structure. Both classes of data are part of the basic set required for comparative planetology; they provide the spatial context for *in situ* surface measurements and allow the extrapolation of such localized measurements to answer planet-wide questions. Comprehensive mapping is facilitated by a low circular orbit, whereas an elliptical orbit may be used effectively to characterize many global properties. Comprehensive mapping in a low-circular orbit by high-resolution remote sensing instruments may seem relatively costly because of needed data rates, spacecraft complexity and propulsion requirements. Science "requirements" that set the number of remote sensing instruments, coverage, spatial resolution, spectral resolution and staging of instrument activity, will greatly affect the mission cost and, therefore, must be carefully examined to provide tradeoffs of "requirements" versus cost.

In situ investigations permit the direct measurement of the properties of surface materials, the interaction of surface and atmosphere, stratigraphic and depositional history, atmospheric composition and evolution, and biological properties. These experiments may be carried out by probes into the atmosphere or to the surface, by soft-landed automated laboratories, or by mobile laboratories. Data obtained by these techniques provide critical ground truth for correlation with mapping by orbital remote sensing. Some processes can only be studied *in situ* at the planet's surface. The return of samples for detailed study and analysis on Earth is by far the most accurate way to make some classes of measurement. However, since sample return does not seem to be economically feasible in the near future, certain key information should be obtained by automated *in situ* instruments to provide early constraints on important planetary questions. New analytical techniques have opened the possibility that useful analyses of volcanic rocks can be obtained by small, short-lived landers targeted to appropriate areas identified using existing orbital photography.

A firm understanding of the internal structure of a planet requires seismic evidence, which cannot be acquired remotely. Seismic study of interior structure requires the establishment of a network of stations that can operate over an extended period of time. It currently appears that such a network (which also is required for meteorological experiments), can best be emplaced by penetrators* or rough landers.

MISSION DEFINITIONS AND PRIORITIZATION: A variety of missions to Mars, Venus, the Moon, and Mercury have been studied—many of them very extensively—at various times. Most of these missions were comprehensive missions in which the science return would have been

* "Penetrators" are missile-like instrumented probes that impact the surface vertically and at high velocity. These probes bury themselves up to several meters deep and relay data to an overflying spacecraft.

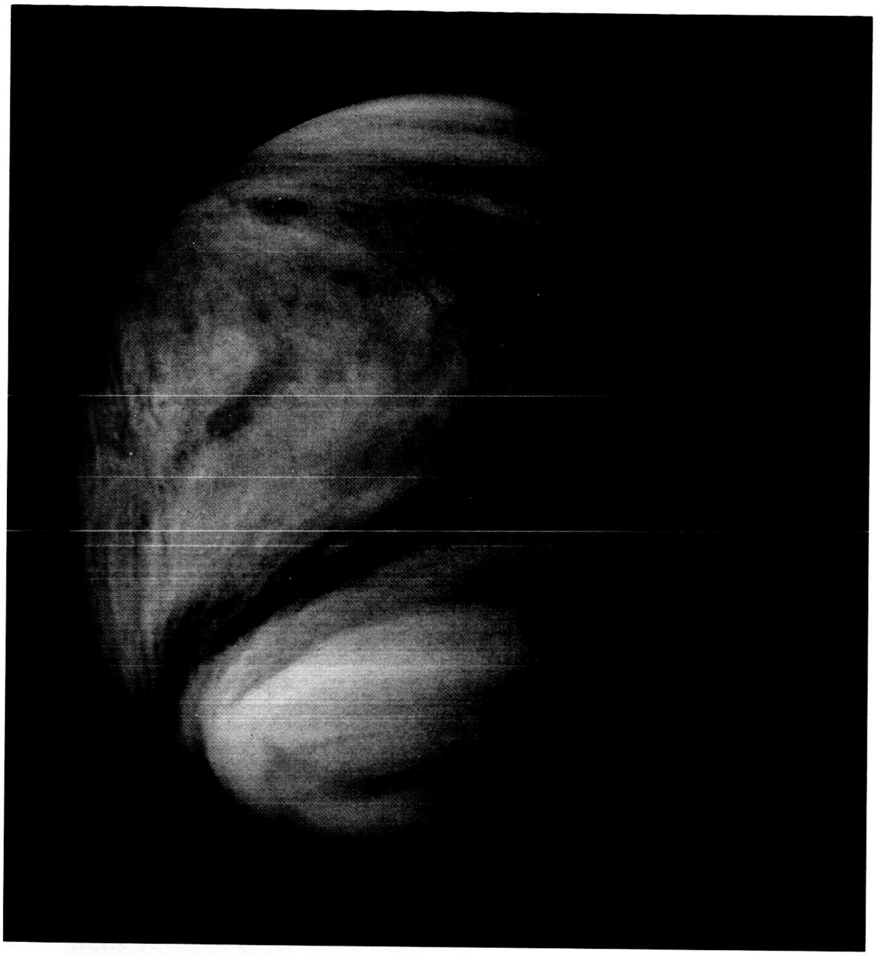
maximized by providing for a complex payload in a logical extension of the *Apollo* and *Viking* experience. The SSEC recognizes that such comprehensive missions provide high scientific value for their cost, but concludes that they cannot be included in a Core program because of their cost. Also for reasons of cost, sample return missions and ones requiring mobile soft landers were excluded. The science goals of these missions are therefore omitted from the goals of the SSEC Core program. Given these major constraints, the Inner Planets Working Groups were asked to define missions to address the highest priority science objectives of terrestrial planet exploration, including a survey of the Moon for both scientific reasons and to provide a lunar resource assay. The Working Groups also were tasked to determine if such missions might be carried out in a cost effective way using Earth-orbital spacecraft produced by the aerospace industry and launched from the *Shuttle* using relatively small upper-stage boosters.

Six such limited-scope missions—*Venus Radar Mapper, Mars Geoscience Orbiter, Lunar Geoscience Orbiter, Mars Climatology Orbiter, Mars Aeronomy Orbiter,* and *Venus Atmospheric Probe*—were studied and are described below. Only a limited set of objectives can be addressed in such simplified missions. It was necessary to exclude some first-rate science that had been identified in earlier studies. In particular, high resolution imaging, despite its scientific value, was excluded because of its high data demands. Also, no subsatellite was included in the *Lunar Geoscience Orbiter* mission to provide gravity field coverage for the lunar far side.

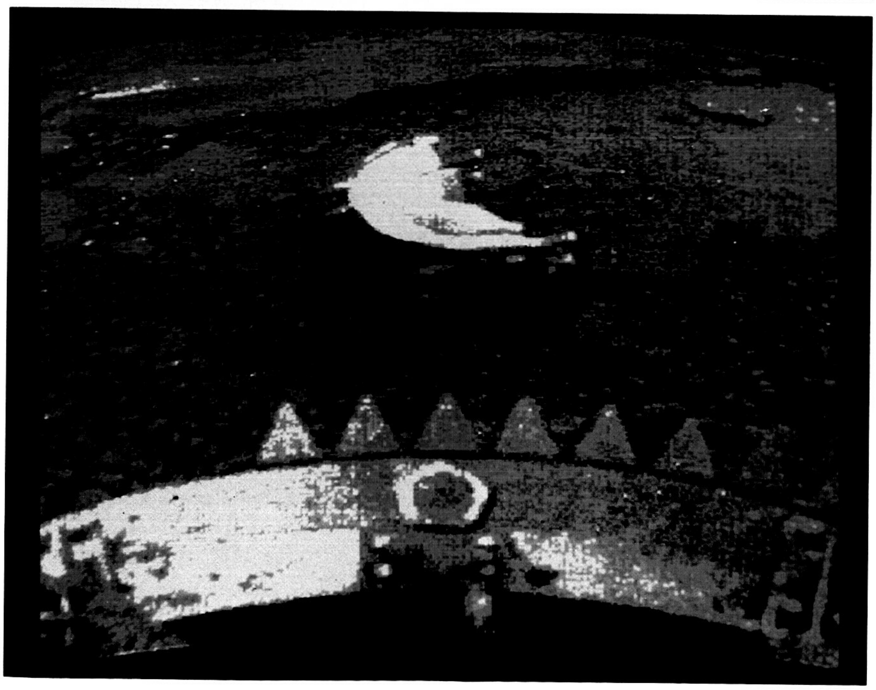
The following sections discuss specific missions to each of the selected, target planets.

VENUS MISSIONS: A principal scientific objective of inner solar system exploration is to understand the nature and evolution of the interiors, surfaces, and atmospheres of the Earth, Venus and Mars. These three planets are of similar size and formed in the same region of the solar system, but have evolved to extremely different present states. As recommended by COMPLEX, the next major step in exploration of the inner planets is the global reconnaissance of Venus' surface features to ascertain the geologic history and the processes by which the surface evolved. Because of the ubiquitous cloud cover on Venus, orbital observation with an imaging radar system is the only feasible approach.

What limited data we have on the nature of the Venus surface is provocative. The *Pioneer Venus* radar altimeter produced topographic and physiographic data on a lateral scale of about 100 km, with 100 m vertical accuracy, between about 75°N and 65°S latitude. The total relief of about 13 km is similar to that on Earth but the distribution of elevations is very different; it is unimodal as contrasted with bimodal. Sixty-five percent of the surface of Venus lies within ±2 km of the mean planetary radius in a province of gently rolling plains, 27% is lowland and only 8% highland. Gravity data from *Pioneer Venus* show a strong correlation of gravitational anomalies with topography at mid-latitudes where the gravitational field has been adequately mapped. Thus, some large-scale topographic features appear to be young, possibly great shield volcanoes, and perhaps dynamically supported by



The ever-present clouds of Venus obscure the planet's surface from the Pioneer Orbiter, *which took this picture from an altitude of 65,000 km.*



This false color panorama of the surface of Venus was taken by the Soviet Venera 13 Lander. *The colors accentuate surface texture differences in the original black and white image.*

upward motion of mantle material. On the basis of *Pioneer Venus* and Earth-based radar studies it appears that one topographic feature on Venus—Ishtar Terra—may be a continental plateau with prominent, linear mountain belts. What appears to be a major rift zone encircling much of the planet at tropical latitudes also has been discovered.

The various Soviet *Venera* missions have provided certain valuable *in situ* data concerning the properties of the surface of Venus. Four images of the surface in the rolling plains province adjacent to or on the flanks of the supposed volcanoes, Rhea and Thea Mons and Phoebe Regio, reveal the presence of small boulders—some of them quite angular with sharp edges—and fine soil at the higher elevations. A multi-layered bedrock surface characterized by multiple thin layers, fractures and cracks was found at the lowest elevation site studies. *In situ* elemental chemistry analyses suggest that the composition of the surface material may be similar to common terrestrial oceanic basalt, except for one example more like the alkaline basalt found at active rift zones or shield volcanoes on Earth.

The nature of the present and past tectonic style on Venus is of fundamental significance. The kind of information we can expect to learn on this issue from a radar mapping mission has been more sharply defined by *Pioneer Venus* radar altimetry, ground based radar telescope observations, and *Venera* imaging data. Although there is a difference of opinion as to whether the crude resolution of the *Pioneer Venus* radar is sufficient to definitively preclude plate tectonics, it is already clear that plate tectonism on the terrestrial scale is not at work on Venus. On the other hand, plate movement and subduction may have developed in the past—perhaps when an ocean was present, as implied by the *Pioneer Venus* composition measurements. The presence of water may be a necessary condition for movement and subduction of lithospheric plates. The dominant method by which Venus dissipates its internal heat energy may have changed from upwelling at mid-ocean ridges to widespread vulcanism when a runaway greenhouse robbed Venus of its ocean. The highland region named Ishtar Terra may be a continent developed during the plate tectonic phase. If that should be the case, the mountain ranges may attest to the fact and there may even be fossil river channels and ancient shorelines around the lowlands that can still reveal the effects of an early Venus ocean. For these reasons it has become abundantly clear that ***obtaining a global map of the surface of Venus with a horizontal resolution of at least one km remains a primary objective of first importance.***

The Committee therefore assigned its highest priority to the *Venus Radar Mapper,* which will provide a global reconnaissance of Venus' surface features equivalent to that carried out for Mars by *Mariner 9*. This mission has been derived from studies of a more complicated, more expensive mission, the *Venus Orbiting Imaging Radar*. The *Venus Radar Mapper* mission has capitalized on a number of cost-saving measures described in an earlier section. While reduced in scope from the original plan for *Venus Orbiting Imaging Radar,* the mission will return essential data needed to continue our comparative studies of Earth, Venus, and Mars. Although coverage and resolution are somewhat reduced, the *Venus Radar Mapper* design now includes several adaptive features which are improvements over the earlier design.

The goals for the *Venus Radar Mapper* are to: 1) obtain a near-global map of Venus using synthetic aperture radar imaging with sub-kilometer resolution; 2) provide global and local topographic information using a radar altimeter; and 3) extend the global gravity field obtained by *Pioneer Venus*.

These measurements by the *Venus Radar Mapper* should permit us to address a number of major questions about Venus:

- What geological processes operate to form and modify the surface of Venus?
- What is the age of the surface of Venus?
- How old is the present atmosphere?
- Did Venus have water and oceans?
- Does Venus have plate tectonic activity?
- What is the origin of the Venus highlands?
- Why are topography and gravity positively correlated?
- How does Venus dissipate its internal heat?
- What can Venus tell us about Earth history?

The *Pioneer Venus* and *Venera* missions raised questions about the Venusian atmosphere that can only be answered by an atmospheric probe instrumented for *in situ* analysis. Verification of the finding of large Ne and ^{36}Ar abundance and large Ar/Kr, Ar/Xe and D/H ratios is needed. Precise values for $^{22}Ne/^{20}Ne$, $^{84}Kr/^{86}Kr$ and $^{132}Xe/^{129}Xe$ ratios are also required to place constraints on theories of origin of planetary atmospheres. Oxidation state of the lower atmosphere, H_2 and H_2O abundances and density profiles for sulfur compounds, H_2S, COS, SO_2 have also been identified as major questions for resolution. Such a probe, which can be based on the *Pioneer Venus* large probe technology, must be equipped with state-of-the-art instrumentation to measure trace gases to accuracies an order of magnitude better than achieved by *Pioneer Venus*. The probe mission would be carried out in a manner similar to that successfully demonstrated by the *Pioneer Venus* mission with the probe being carried to Venus on a simple bus and with direct relay of the data to Earth.

MARS MISSIONS: Since 1978, when the COMPLEX report on the inner planets was published, a large volume of data has been returned by the *Viking Landers* and *Orbiters*. These data are slowly being reduced and analyzed—not just by the selected *Viking* scientists but by the entire planetary sciences community. The continually enlarging body of knowledge about Mars confirms the recommendations made by COMPLEX and has added emphasis to the importance of identifying the volatile sources and sinks and of understanding the nature of their interaction with the atmosphere and their impact on Martian climate.

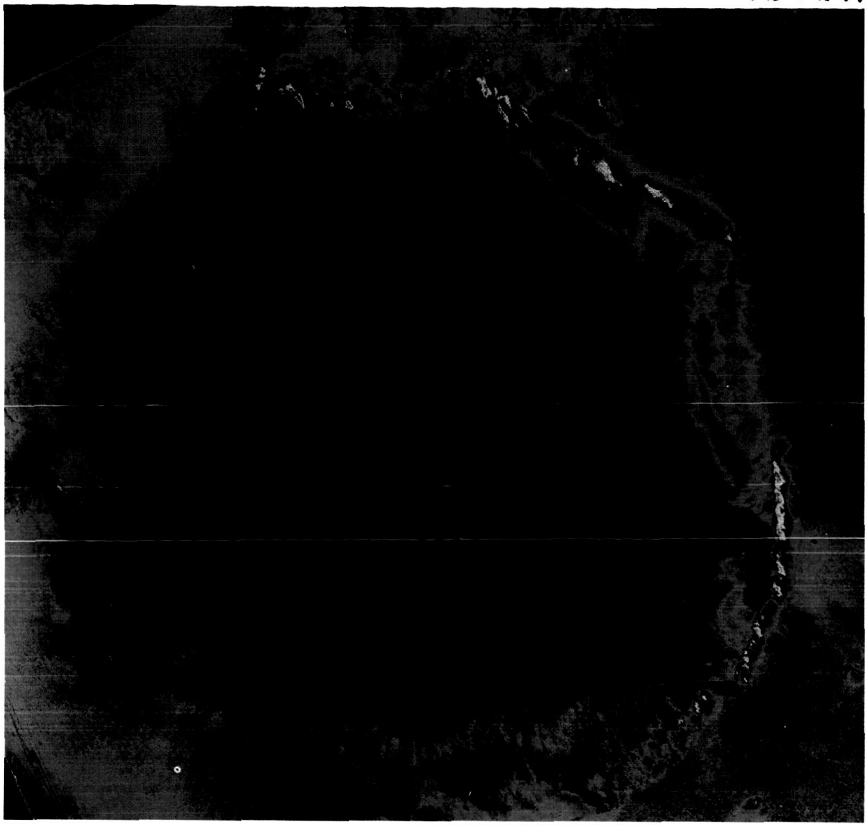
Although the science priorities established by COMPLEX for Mars remain valid, the guidelines established by the SSEC for the Core planetary program prevent including missions capable of addressing the highest priority science objectives, specifically sample return and

mobile lander missions. However, many high priority objectives basic to understanding Mars and the inner solar system are attainable within our guidelines:

- Characterize the internal structure, dynamics and physical state of the planet;
- Characterize the chemical composition and mineralogy of surface and near-surface materials on a regional and global scale;
- Determine the chemical composition, mineralogy, and absolute ages of rocks and soil for the principal geologic provinces;
- Determine the interaction of the atmosphere with the regolith;
- Determine the chemical composition, distribution and transport of volatile compounds that relate to the formation and chemical evolution of the atmosphere and their incorporation in surface rocks;
- Determine the quantity of polar ice, and estimate the quantity of permafrost;
- Characterize the dynamics of the atmosphere on a global scale;
- Characterize the planetary magnetic field and its interaction with the upper atmosphere, solar radiation, and the solar wind;
- Characterize the processes that have produced the landforms of the planet;
- Determine the extent of organic chemical and biological evolution of Mars and explain how the history of the planet constrains these evolutionary processes; and
- Search for evidence of the signature of the early atmosphere in ancient sediments.

Various models have been developed in each of these areas but, necessarily, they are based on the extrapolation of inadequate data. Real progress in our understanding requires additional data acquired with state-of-the-art instrumentation. The significance of these objectives and the recommended approaches to achieve them will be discussed below.

GEOSCIENCE ORBITER: The goal of mapping the elemental and mineral composition of the surface of Mars on a global scale with a spatial resolution of tens to hundreds of kilometers is a basic requirement to allow the surface history of the planet to be deduced. We already have available sub-kilometer resolution global maps of Mars acquired by orbital imaging systems, together with substantial areas of imaging coverage with resolution better than 100 m. These maps are the legacy of the *Viking Orbiter* missions and are the subject of intense geological analysis using standard photogeologic techniques. Compositional data—both elemental and mineralogical—will provide new dimensions to these studies. Such information can be acquired from a low altitude, polar orbiter. Mineralogical data are provided by high spectral resolution mapping coverage at visible and near infrared



The largest known volcano in the solar system, Olympus Mons, which rises over 26 km above the Martian plains, was photographed by **Viking Orbiter 2.** *This false color representative enhances the boundaries between different sequences of lava flows that once spewed out of its mouth.*

wavelengths. Elemental data are provided by gamma-ray spectroscopy. Elemental composition maps were produced for the equatorial regions of the Moon by a first generation gamma ray instrument on the *Apollo* command modules. Though limited in coverage range, the *Apollo* data allowed the identification of localized regions with compositions like some rare lunar rock samples, those rich in potassium, rare-earth elements and phosphorus. With such compositional data the boundaries of different geologic units can be fixed much more definitively, subtle similarities and differences can be identified, and direct inferences about the chemistry of the underlying mantle can be made. As on the Moon, local anomalies on Mars that may carry highly significant information about the evolution of the interior can be identified. Moreover, the data set acquired in this way will provide us with a substantial improvement in our ability to specify sites for future landers and sample return vehicles.

A low altitude polar orbiter is also well suited to address other key geoscience objectives—the determination of the nature of any Martian magnetic field, and the global measurement of surface elevation variations to provide the "figure" of Mars and the vertical profile of surface features. To date, we rely primarily on Earth-based radar and on synoptical imaging taken from a variety of directions to determine the global shape of Mars and on convergent stereoscopic coverage to determine the vertical scale of the volcanoes, canyons, and channels that characterize the surface. A low altitude polar orbiter with a simple radar altimeter, a magnetometer, and Doppler tracking would acquire a comprehensive, high precision data base that could be applied to numerous basic geological and geophysical problems.

C-2

CLIMATOLOGY ORBITER: The meteorological, compositional, and morphological data acquired by the *Viking* orbiters and landers since 1978 have accentuated the important role played by volatiles in the evolution of Mars and in the characterization of its present state, particularly its climate. There is good evidence that the atmosphere once held at least ten times as much carbon dioxide and nitrogen as it does at present. A 25% inter-annual variation in surface pressure is clearly correlated with the release and condensation of carbon dioxide at the polar caps. There are also seasonal oscillations in water vapor with much larger amplitude at high latitudes than at low latitudes or in the south. Thus, the passage of volatiles into and out of sinks—basically the Martian hydrological and carbon dioxide cycles—appears to be one of the important features of Martian climate.

The available data set (mostly from the *Viking Orbiters*) for the study of such problems consists primarily of limited synoptic imaging data together with infrared maps that allow the atmospheric water vapor content and the surface temperatures to be determined. Because of the constraints arising from the requirement for the *Viking Orbiters* to provide a telemetry link with the two landers, the data set is spatially and temporally incomplete. To these data we can add also the *Viking Lander* measurements of the seasonally varying atmospheric pressure as the polar caps wax and wane (these caps contain a portion of the principal atmospheric constituent, carbon dioxide). Pressure measurements provide us with the opportunity to identify the onset of global dust storms through the characteristic pressure variation "signature" of such storms definitively observed in orbiter images.

Once again, we possess a data set that allows the framing of numerous basic questions but frustrates our ability to answer them because of incompleteness in time and coverage. Substantive progress calls for the assembly of a systematic body of data for a period of at least one Martian year, 687 days. The needed measurements would record the expansion and shrinkage of the polar caps, allow the distinction between water ice and carbon dioxide ice on the surface, provide evidence of seasonal hydration and dehydration of surface minerals, and allow the seasonally and regionally variable water vapor content of the atmosphere to be inferred. These data could all be acquired from a suitably instrumented spacecraft in an orbit identical to that needed for measurements of surface composition on a global scale. Indeed, the composition-measuring instrumentation on such an orbiter would also be required to undertake certain climatological measurements. Specifically, an infrared reflectance spectrometer would be essential to measure the degree of hydration of surface materials and to identify frost and ice. The role of the gamma ray spectrometer in the climatological investigation would be to determine the nature of the small permanent polar caps. From *Viking Orbiter* observations, these caps are known to display quite different temperature characteristics during the summer months—the northern cap appears to be made of water ice while the southern cap may be carbon dioxide ice or a mixture of both (a "clathrate").

GEOSCIENCE/CLIMATOLOGY ORBITER: Missions to meet the geoscience and climatology objectives described above share a common orbit and several similar or identical instruments. *Geoscience* and *Climatology* missions were defined to test whether they could be carried out by very small, inexpensive industry spacecraft and launched with an already deployed small upper stage or "payload assist module" *(PAM-A)*. In general, the industry studies show that the missions require a somewhat more capable spacecraft and a larger upper stage. A solid rocket stage derived from the inertial upper stage *(IUS)* and already under development for the deployment of communication satellites—the *SRM1*—would suffice. In most cases this also results in margins for propulsion, payload and data rate beyond those required to accomplish the limited objective mission. We find that the *Geoscience* and the *Climatology* missions can be effectively combined into a single mission with a six-instrument, baseline payload: 1) gamma ray spectrometer; 2) mapping reflectance spectrometer; 3) radar altimeter; 4) magnetometer; 5) thermal IR radiometer/spectrometer; and 6) U.V. spectrometer/photometer. This combined mission is assigned the next highest priority, after the *Venus Radar Mapper,* among the inner planets missions on account of the importance and range of the science questions addressed and because it provides an excellent basis to demonstrate the use of Earth-orbital spacecraft derivatives for planetary exploration.

AERONOMY ORBITER: Additional high priority objectives identified by COMPLEX are the determination of the character of the Martian magnetic field, the nature of the planet's interaction with the solar wind, and the structure and dynamics of the upper atmosphere. These objectives require an orbit significantly different from that needed for the geoscience and climatological studies previously discussed. Magnetic field measurements from the two spacecraft would be complementary. The low altitude *Geoscience Orbiter* would measure any intrinsic field directly while the *Aeronomy Orbiter* would measure the magnetic field fluctuations that characterize the impacting solar wind.

The interaction between the solar wind and the upper atmosphere presents a host of fundamental problems: major issues include the physical processes that lead to mass exchange between the atmosphere and the solar wind and the resulting atmospheric mass loss (or gain) rates. Such processes, which lead to atmospheric escape or accretion, are essential to our understanding of the evolution of the Martian atmosphere, as we know from the *Viking* measurements of fractionation of atmospheric species.

Determination of the distribution of neutral atmospheric constituents together with the distribution of ionized plasma and charged particles is needed. The orbital characteristics required are those that allow measurements to be made in the dayside interaction region at about 300 km altitude, on the nightside of Mars, and in the downstream magnetosphere to a distance of several Mars radii. Studies have shown the suitability of modified Earth-orbital spacecraft for such a mission. The science payload would be similar in scope to

that of the *Pioneer Venus Orbiter*, which made comparable measurements at Venus and left Mars as the only terrestrial planet where the properties of the magnetosphere and the solar wind interaction region are essentially unexplored.

Orbital missions also could make an important contribution to the determination of the general circulation of the atmosphere, a requirement for understanding the present climate of Mars as well as for comparative meteorological research. We already have a first order knowledge from *Viking* of how the Martian atmosphere responds globally to solar heating. At certain times of the year the circulation resembles that of the Earth's atmosphere with a marked jet stream and continental-scale, traveling eddies that transport heat from equator to pole; at other seasons the circulation is markedly different. Unfortunately, our knowledge is highly incomplete because the two *Viking* weather stations and two supporting orbiters simply could not acquire an adequate global data set. The highest priority information that might be acquired from an orbiter is the spatial and temporal variation of atmospheric temperature and pressure with altitude. A daily, global data set could be gathered using a downward looking infrared radiometer to "sound" the atmosphere.

NETWORK MISSION: To make more substantial progress in studies of Martian meteorology, we must go beyond remote sensing orbital measurements and establish a network of landed stations. For a definitive determination of the Martian global circulation, several tens of stations would be required, distributed evenly about the planet. Major improvements in our knowledge could be achieved with only a few stations, less than ten if appropriately sited.

A surface network of hard landers of the kind needed to establish weather stations would also provide the basis for a seismic study of the Martian interior. Only a seismic study can ascertain the interior structure of the planet and establish the presence or absense of a core.

The *Viking* seismic experiment was aimed at providing a measure of the seismic activity on Mars and not at a determination of the internal structure of the planet. With only one working instrument, the *Viking* data were sufficient simply to establish that Mars is much less active than the Earth (no quakes were definitely measured) and to demonstrate the serious problem presented by wind-induced noise, which limited seismic data gathering to the quiet night hours. COMPLEX recommended, and the Working Group concurs, that a passive seismic network should be established on the Martian suface, consisting of at least three stations with broadband sensors, each with a sensitivity at least 100 times better that *Viking's*, spaced about 1000 km apart and operating for at least one year. These sensors should be coupled to the surface to measure seismic activity rather than meteorological information.

In the absence of returned samples or mobile surface laboratories, a network of hard landers, established primarily for meteorological and seismic research, could also provide an excellent source of geochemical data. Various sensors have been developed to provide a measurement of the elemental composition of surface materials: miniaturization of this instrumentation has already been

demonstrated. The data acquired in this way could provide not only ground truth for orbital measurements but could achieve much greater precision for both major and minor chemical elements, thereby substantially enlarging the scope of the geochemical investigation of Mars that is possible within the Core program.

Several high priority science objectives can be achieved by a *Mars Network* mission by establishing a global network of combined seismic stations, meteorological stations, and geochemical and geophysical observation sites; these stations can operate on Mars for the long periods of time needed for seismic and meteorological experiments. The mission objectives can be accomplished through the emplacement of hard landers or penetrators. The penetrator and its afterbody can contain a wide variety of instruments. Their unique advantage is in their emplacement into the ground, where they create a solid seismic coupling and where geochemical instruments can conveniently measure composition.

The prime purpose of such a network mission is to determine the general circulation of the Martian atmosphere, to characterize the climatology of surface conditions in different Martian regimes, to characterize the seismic properties of the planet, and to make geochemical analyses. Heat flow measurements would also be desirable but the experimental technique requires development. A very large network is desired to fully characterize the general circulation. The other objectives can be addressed by a minimum of three to six stations. Instruments would include seismometers and heat flow sensors in the forebody, and pressure, temperature, and wind sensors and a nephelometer* in the afterbody. Mission cost estimates indicate that a network of about six penetrators could be deployed and serviced by a simple orbiter for a year for a total cost of about $200M. This places the mission into the upper end of the general cost category occupied by the other inner planet missions, which will be undertaken using Earth-orbital derivatives. Because more development is still needed, the Working Groups do not recommend that the *Mars Network* mission be undertaken in the near term.

SURFACE PROBES: A surface probe mission of simpler scope is, however, a high priority. The measurement of bulk chemical composition, including key trace elements, would be the primary goal. New analytical instruments and a well-studied cosmochemical model relating the composition of basaltic volcanic constructs to that of the planet make the goal of determining bulk composition open to missions using penetrators or rough landers. The key objective is to obtain elemental analyses of volcanic rock, including key trace elements and light elements. An additional objective is the analysis of ice cap material and sub-surface permafrost material. Gamma-ray analysis has been used on space missions to measure the abundance of naturally radioactive elements (potassium, lanthanum, lutetium, thorium, and uranium) and elements activated by cosmic rays (iron, magnesium, titanium, oxygen, silicon, etc.). A wide variety of additional elements can be analyzed by using a pulsed neutron generator. Such an instrument installed in a penetrator can analyze a

* A "nephelometer" measures the characteristics of atmospheric condensate and dust particles, typically through the observation of scattered light.

sub-surface volume about one meter in diameter and would require only a short period of detector cooling and data transmission. Such a simple penetrator development would be an excellent precursor for an eventual network of more complexly instrumented penetrators. Penetrators can be released upon approach to Mars and targeted for volcanic areas identified on the existing images. The actual landing location could be determined by tracking, by nested entry images, or afterbody imaging. Data would be transmitted to an orbiting spacecraft for relay to Earth: the orbiter might be an earlier mission spacecraft or might be the simple uninstrumented probe carrier.

LUNAR MISSIONS: Noting the scientific accomplishments arising from the *Apollo* program, and in line with its policy that study of planetary bodies should be kept in balance, COMPLEX assigned a complementary role to continued study of the Moon. From *Apollo* we know that the Moon formed early in solar history and soon began chemical separation to produce the highlands crust. Some half billion years later, giant impacts produced the mare basins, which flooded with lava. Production of lava ceased when the Moon was about 1.5 billion years old. The lithosphere is thick (about 1000 km) and moonquake activity is very weak. The heavily cratered surface is covered with crushed rock. The center of gravity is offset about 2 km from the center of mass. There is no detectable global dipole field, but weak magnetism is observed at the surface and in rocks.

When the COMPLEX report was produced, our understanding of lunar evolution was primitive and our models were simple. Supposedly, the Moon melted rapidly to form a magma ocean 300 km deep. This ocean precipitated iron-magnesium rich minerals onto its floor to produce igneous cumulates. The ocean fractionated chemically—calcium, aluminum-rich plagioclase crystallized and floated to form a crust. Later, impacts excavated basins which flooded with lavas produced by remelting of the deep-lying cumulates. Continuing studies of soil and breccia fragments, however, have indicated a wider variety of igneous rocks than can be produced by a simple magma ocean. Uncomplicated derivation of mare lavas by remelting of cumulates is unlikely. Our perception of the Moon's development has therefore changed; its history is more complex than initially thought.

It is necessary to further our understanding of the Moon's early history as a scientific objective in its own right and also because of the impact such understanding would have on the general scientific goals of planetary exploration. Interpretation of surface and differentiation histories for many planetary bodies depends on analogy with the Moon's history. A magma ocean is a tight constraint on heat sources for planets, requiring short-lived radioactivity or very rapid accretion. With no magma ocean, these constraints are relaxed. Understanding the Venus-Earth-Mars triad includes the Moon's role in Earth's development; the Moon is large in proportion to Earth and may have affected Earth's evolution.

The Moon's proximity to Earth makes it the most plausible first source of materials for use in space. Evaluation of near-Earth resources is a recommended goal for planetary exploration.

Scientist-Astronaut Harrison Schmitt explores the strange, orange-colored soil found at the Apollo 17 *Taurus-Littrow landing site.*

Assessment of the Moon's resources depends on how confidently we can extrapolate our knowledge of surface rocks. It depends on new data; for example, whether water and other volatiles are frozen in permanently shadowed regions at the poles. The availability of water would make a fundamental difference in how lunar resources are used and where the first base is located.

These goals require more accurate understanding of the Moon's evolution than we can develop from the present data. The most pressing needs are global maps of surface composition, gravity field, and magnetic patterns; imaging; and broader seismic coverage. Present remotely sensed data are far from comprehensive and do not match in quality those anticipated for other planets, for example, Mars. Imaging quality is mediocre for much of the Moon and there are no images for polar regions where volatiles may be. Coverage is incomplete for Mare Orientale, the prime mare for detailed structural study. Similar basins surely had a role in Earth's history. The Earth's oldest rocks (about 3.9 billion years) have the same age as the lunar maria. Is this a coindence?

Geochemical and near-surface magnetic sensing are limited to the *Apollo 15* and *16* groundtracks, only 20% of the surface. Geochemical sensors were primitive, yielding only a general idea of surface compositions. Extrapolation of "ground truth" from acquired samples is therefore crude. No samples were taken from typical lunar

highlands terrain. Every mission found new rock types, so we can reasonably assume that sampling is still incomplete. Remote sensing indicates higher titanium in the highlands than in sampled highland soils except where basalt from nearby maria is mixed in. On the farside, there are no large maria, so the source of titanium is a puzzle. We lack geophysical knowledge of highlands crust. Inference of a thick, plagioclase-rich crust on the farside rests on the magma ocean model and non-unique interpretation of the offset between centers of figure and mass. A broad seismic network is required to determine the Moon's internal structural complexity and whether there is a core.

Thus, the Moon is largely unexplored from geological, geochemical, and geophysical points of view. Global exploration similar to that described for Mars is needed. Of highest priority is the *Lunar Geoscience Orbiter*, to obtain global maps of surface chemical composition, topography, and small-scale variations in gravitational and magnetic fields. *Planetary Observer* class missions for the future should include imaging and rough landers to establish a geochemistry-seismic network. These may be needed for planning for a U.S. lunar base, which may be emplaced toward the end of this century.

In keeping with COMPLEX priorities and consistent with SSEC goals to survey near-Earth resources, the Committee includes the *Lunar Geoscience Orbiter* in the Core program. Specific objectives and anticipated instrumentation are given below. The *Lunar Geoscience Orbiter* will provide first order data on the Moon's surface composition, including whether there are trapped volatiles at the poles. It will provide the first look at compositions for 80% of the surface. It will provide information of local gravity anomalies which, with imaging and composition, indicate how individual regions developed tectonically and chemically. It will provide a global map of surface magnetic properties for better understanding of the Moon's localized, seemingly random fields. All these are crucial input for more realistic models for early planetary history.

The Committee notes the commonality between orbiter missions for geoscience study of Mars and the Moon. A lunar mission can thus be undertaken as a follow-up to a Mars mission for marginal additional costs. In addition, rendezvous missions to Earth-approaching asteroids could use spacecraft similar to the Mars and lunar geoscience orbiters.

MERCURY MISSIONS: Our present knowledge of Mercury, based primarily upon astronomical observations and the *Mariner 10* mission, is not as advanced as that for Mars, the Moon, and Venus. Improvements in this base of knowledge gathered by geoscience missions to Mercury will contribute to increased understanding of several major science phenomena including: planetary condensation as a function of position in the nebula during formation of the solar system; thermal evolution of small, dense bodies in the solar system; bombardment chronologies as a function of position in the solar system; origin of planetary magnetic fields; solar neutron production; and non-Newtonian, metric gravitation theories. Mercury science objectives can be best addressed by a polar orbiter with geochemical, geophysical, and geologic instrumentation, augmented with several mission-specific instruments (e.g., solar neutron detector).

In setting scientific priorities COMPLEX placed Mercury in a secondary position relative to Mars and Venus. There are also important technological reasons (launch energy required to reach and orbit Mercury, and thermal control) why Mercury missions would be difficult to include in any planetary program operating within tight budgetary constraints. Therefore no Mercury missions are recommended within the Core program. However, a Mercury multi-flyby with *Venus Atmospheric Probe* might be a candidate for international cooperation: the probe could be inserted during a Venus swing-by as the spacecraft proceeded toward Mercury for a series of flybys. Remote-sensing instruments could achieve nearly global coverage of Mercury during these multiple flybys.

Summary of Recommended Missions

VENUS RADAR MAPPER
- First priority
- Launch 1988/Arrive 1988
- 243-day orbital mission
- *Galileo-Voyager-ISPM* derivative spacecraft
- *Shuttle-Centaur* launch vehicle
- First high resolution map of surface

MARS GEOSCIENCE/CLIMATOLOGY ORBITER
- Second priority
- Launch 1990/Arrive 1991
- 687-day orbital mission
- *Planetary Observer*
- *Shuttle-SRM 1* equivalent launch vehicle

LUNAR GEOSCIENCE ORBITER
- *Planetary Observer*
- *Shuttle-PAM-A* equivalent launch vehicle
- One-year orbital mission
- Instrumentation similar to *Mars Geoscience Orbiter*
- Addresses both science and resource goals

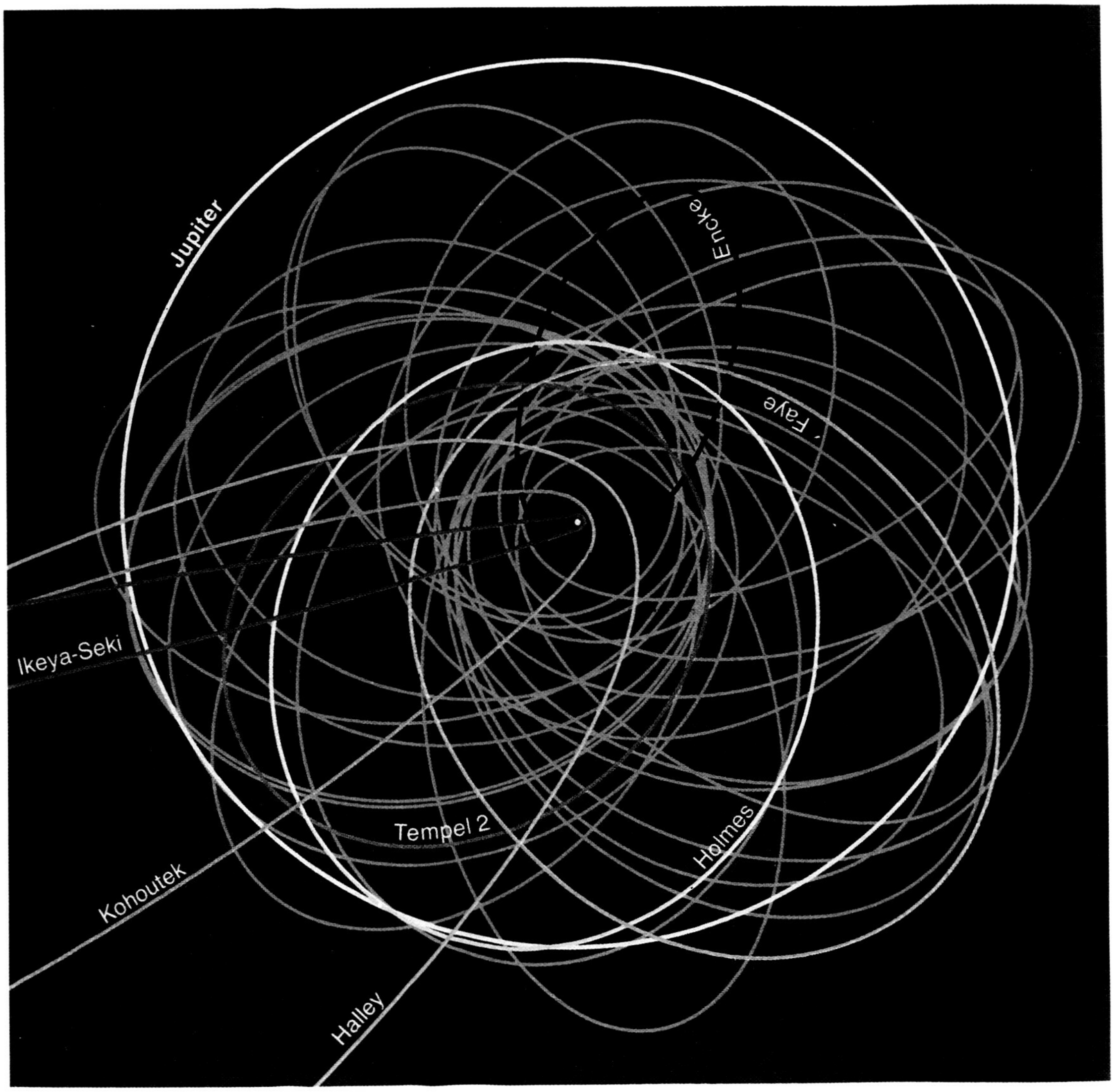
VENUS PROBE
- *Planetary Observer* bus plus entry probe
- *Shuttle-PAM-A* equivalent launch vehicle
- Six-month trip time

MARS SURFACE PROBE
- *Planetary Observer* bus/orbiter plus penetrators
- *Shuttle-SRM-1* equivalent launch vehicle
- Communications through orbiter

MARS AERONOMY ORBITER
- *Planetary Observer*
- *Shuttle-SRM-1* equivalent launch vehicle
- 687-day orbital mission
- Instrumentation similar to *Pioneer Venus Orbiter*

Small Bodies

SCIENTIFIC BACKGROUND: Comets and asteroids compensate for their diminutive size by their numbers: there are more than 500 Mainbelt asteroids over 50 km in diameter and thousands that are smaller; the inferred number of cometary nuclei in the so-called Oort Cloud is almost beyond count (10^{10} - 10^{12} by some estimates). Comets have been respected and feared over the centuries because of their sudden, phantom-like appearances in the night sky. They have been superstitiously linked with many human dramas and catastrophies. More recently, we have come to realize that comets and asteroids do in fact pose a real threat to our planet—fortunately one that is measured



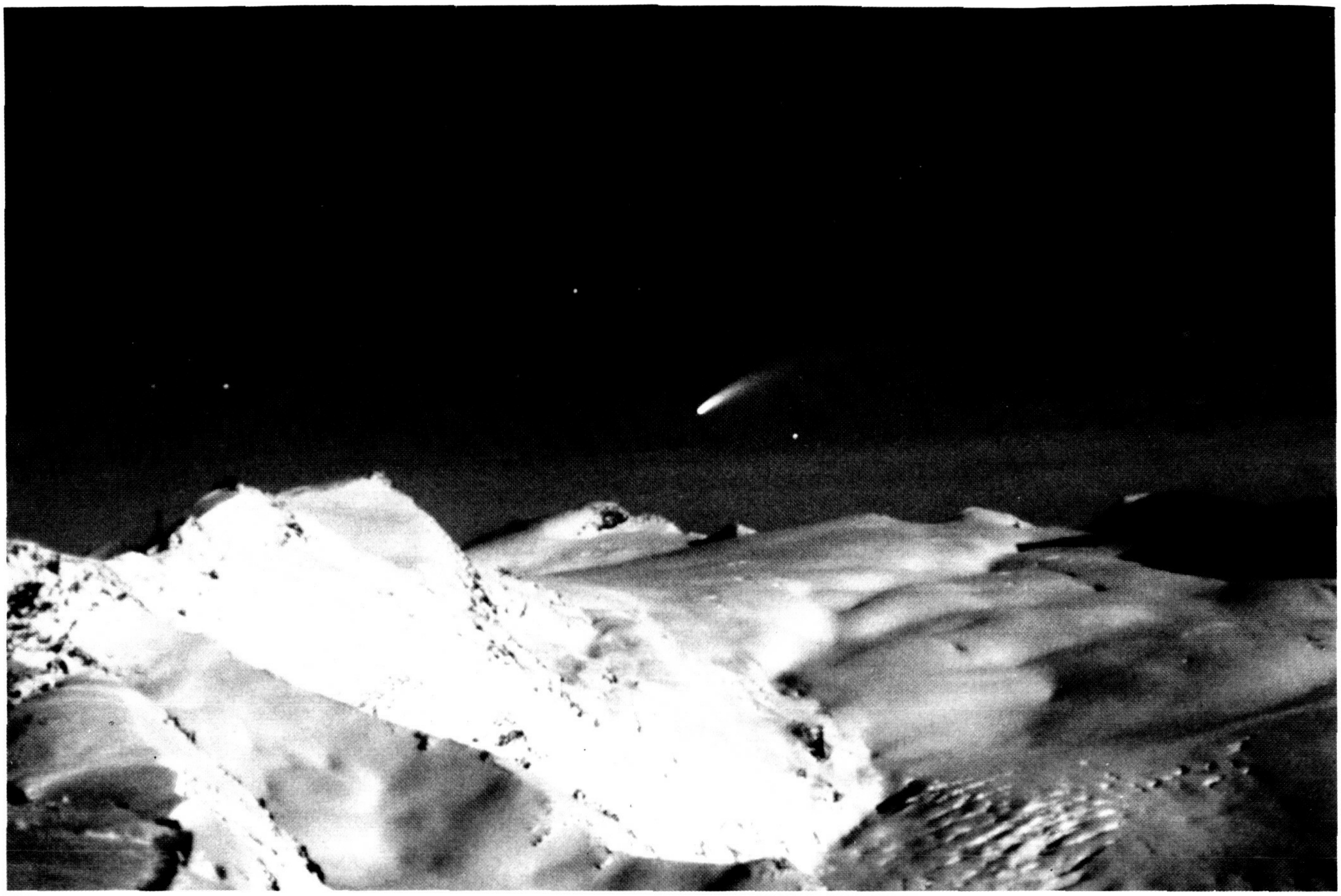
The tightly-woven orbits of many of the known comets—including the famous Halley—are depicted in this drawing.

on geological time scales—because the orbits of some of these bodies intersect that of the Earth and collisions inevitably occur. Since the population of these Earth-crossing bodies is maintained in essentially a steady state by transfers from storage in the cometary Oort Cloud and from the asteroidal Mainbelt, occasional collisions will continue to occur. The eventual understanding of these small bodies will illuminate our planet's history, including cometary contributions to the early atmosphere (and, even, to the origin of life), and the connection between impacts and the extinction of species.

Comets and asteroids have an even more fundamental role to play in solar system science, as the best preserved remnant materials dating from formative epochs. In studying the terrestrial planets we are denied the opportunity to look back to the very beginning because all of them have evolved greatly. The outer planets seem more promising since they are thought to have changed little since they were formed; nevertheless, since we can only sample the "skin" of the gas giants we must inevitably rely upon modeling to extrapolate our findings. Comets are probably the least differentiated and best preserved products of processes that occurred in the preplanetary solar nebula, at least in their outer solar system places of birth. Because they have been stored in a frozen state of suspended animation far beyond the planets, we hope to be able to use cometary compositions and structures to read directly the formation events of the solar system. Most asteroids are analogous primitive products of solar nebular condensation and accretion processes in the Earth-Mars-Jupiter region of the solar system. But others have undergone substantial evolution, albeit during the earliest phases of the solar system's history; some asteroids are even expected to prove to be pieces of the cores of once-larger differentiated objects, melted by unknown early heat sources and subsequently broken up by collisions. From spectroscopic studies we know that there are definite trends in asteroid compositions across the Mainbelt, which forms a transition region between the inner (rocky) planets and the outer (gaseous and icy) planets. Thus, the asteroids provide a perfect complement to the utterly primitive cometary denizens from unknown parts of the outer solar system. The asteroids are a mixture of primitive and evolved objects in an apparently preserved ordered structure related to the original temperature/pressure distribution of the inner solar nebula.

Given the large number of different compositional types of small bodies that have been classified by planetary astronomers, it might seem to be an insurmountable task to make all the necessary connections in the puzzle if analysis of returned samples from a large number of widely separated comets and asteroids were necessary. Happily, we already have access to samples—meteorites—broken off from some asteroids (and possibly some comets) by collisions and, in time, placed on an impact trajectory with the Earth. The major connection that we require, therefore, is the link between the asteroids (both the Mainbelt objects and the Earth-crossing objects that probably include some dead comet nuclei) and our meteorite samples: which are the parent bodies of the meteorites, and what are the larger geological and geophysical contexts from which our samples have been derived? These connections can be made by a spacecraft survey of

Comet Bennett streams its vivid tail over the Swiss Alps in 1970.



representative asteroids, augmented by continued improvements in the Earth-based characterization of the larger populations of comets and asteroids and by continued theoretical research on the processes that liberate meteorites from their parent bodies and deliver them to Earth. Thus, there is good reason to believe that these links can be forged.

Our confidence that the time is ripe, indeed overdue, for the exploration of the small bodies is based upon an ever widening body of knowledge derived from telescopic surveys and from the analysis of meteorites and cosmic dust. Already we can provide plausible models of the nature of comets and asteroids. Most current thinking about comets is based on the "dirty snowball" model in which the nucleus is a mixture of ices and silicates. Cometary nuclei can hardly be observed even using the largest telescopes; they are either too distant and faint or else they are imbedded deep within the huge gaseous, dusty head of an active comet closer to the Sun. The sizes of comet nuclei are difficult to estimate, although two have now been measured by radar (sizes probably range from 1-10 km, typically). The characteristic coma/tail phenomena are in evidence for only a matter of weeks when the comet is nearest to the sun. During that time—when the comet has developed an atmosphere—spectroscopic techniques can be used to measure the constituent species. All of the well-observed species are believed to be

only "daughter" molecules formed when the "parent" molecules expelled from the heated nucleus interact with the solar ultraviolet radiation. The interactions take place very close to the nucleus and parent molecules are therefore extremely difficult to observe. The chemical reactions in the coma near the nucleus are evidently complex. A mystery still surrounds the mechanism by which ionized species are formed, since solar ultraviolet light is not an adequate ionization source.

From spectrophotometry and from the observations of cometary behavior as a function of distance from the Sun (and hence temperature) it has been established that water is an abundant constituent of cometary nuclei. The same data also indicate that some other more volatile species (perhaps CO_2) can also play a role in controlling the activity of some comets as they advance toward and retreat from the Sun.

Dust particles expelled from the nucleus are blown away, more or less directly outwards from the Sun, by solar radiation pressure to form an elongated tail seen in scattered sunlight. Estimates have been made of the relative abundances of dust and ices in comets, based on the observed tail and coma brightness, and have led to the conclusion that cometary nuclei contain up to ten times more icy, volatile material than the most volatile-rich meteorites; comet formation at very great distances from the Sun is implied. The dust component of comets promises to provide us with a sensitive test of cometary origin. Some of the dust may be unaltered interstellar material displaying, through characteristic elemental isotopic ratios, the signature of its formation process. As a good example of an element whose isotopic ratio varies with source, the carbon ratio $^{12}C/^{13}C$ ranges from as low as 2 for certain carbon stars, to 12-50 for red giants, to 90 for our sun and for other solar system objects. Such elemental measurements could be made by *in situ* dust collection and analysis or by the acquisition of a return sample.

A second type of cometary tail is also formed—a tail of ionized gases accelerated away from the nucleus by the solar wind's magnetic field. This plasma tail is made visible by the emission of light as the ionized gas relaxes to lower energy states: the spectra of CO^+ and H_2O^+ dominate. The ion tails of comets often show complex time variability presumed to occur in response to changes in solar wind conditions providing a unique natural probe of the solar wind. *In situ* spacecraft measurements of the ionized envelope of an active comet will determine the nature of the interaction of the solar wind and cometary plasma while frequent, repetitive time-lapse imaging by the approaching spacecraft will provide a key data set for studying the behavior of the solar wind.

Unlike comets, asteroids exhibit a dynamical structure that probably remains from their origin in the regions between Earth and Jupiter. Gaps in their distribution of orbital elements are due mainly to Jupiter's gravitational perturbations, which probably were particularly effective during the earliest epochs of accretion. Asteroids are also clumped into families by orbital parameters. Telescopic observations of family members often reveal great homogeneity, which tends to confirm the old idea that such a family represents the

fragments of one collisionally disrupted, precursor body. It is intriguing that some other families fail to show compositional homogeneity, suggesting that they may have been derived by break-up of a chemically differentiated body. Study of such fragments could be our first direct observation of the interior of a planetary body.

The variation of asteroid composition with distance from the Sun is strikingly revealed by recent telescopic surveys. The inferred compositions—similar to certain types of meteorites—are suggestive of the expected kind of variation in solar nebular condensates in early epochs, with carbonaceous, water-rich asteroids located farthest from the Sun. A significant mystery, however, concerns a small fraction of asteroids that appear to have melted and geochemically differentiated; these asteroids depart radically from their much more common, primitive neighbors. Because of the difficulty in retaining heat in such relatively small planetary bodies, it is not clear how they could have been melted. We must assume that there was a very powerful, if short-lived, heat source. Study of such asteroids might reveal more about the heating episode, which surely also profoundly affected the new-born major planets or the planetesimals from which the planets were made.

The single greatest challenge to our hopes to use asteroids as probes of early processes in the inner solar system is the subsequent collisional interactions of asteroids (comets have been less affected by collisions). It is now a topic of intense interest to study the aspects of asteroids that indicate, albeit indirectly, the degree of collisional evolution they have suffered: their spins, size-distributions, shapes, family structures, possible satellites, etc. If asteroids were thoroughly smashed and their fragments not well-dispersed but rather reaccumulated onto themselves, then asteroids could present some of the characteristics of the lunar megaregolith*. On the other hand, if asteroids efficiently eject fragments of themselves into space during collisional events, then relatively pristine samples (even from the deep interiors of precursor bodies) may be available for study of composition and primordial physical and geological structure. Thus the characterization of the effects of collisional evolution is a first-order priority for initial spacecraft exploration of asteroids.

Although asteroids are often pictured as resembling the Martian satellites Phobos and Deimos, in truth we know nothing about what an asteroid will look like close-up. Even if Phobos and Deimos are captured asteroids, their long evolution deep in the gravity well of Mars surely has altered their properties. For example, we confidently expect that these moons reaccumulate much of the material ejected from their surfaces by cratering; in the asteroid belt, of course, such ejecta are permanently lost. Also, grooves on Phobos testify to other processes that may be due chiefly to the proximity of massive Mars. There is evidence, not yet confirmed, that some asteroids may exhibit very unusual configurations: some may be double bodies, others may have a satellite, or even a retinue of satellites. The potential for identifying such unusual configurations or discovering other totally unexpected traits of this never-before-studied class of objects promises much excitement once spacecraft exploration of asteroids begins. It is

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* The "megaregolith" is approximately the top kilometer of the lunar surface.

Introducing Some Small Bodies

Individual comets and asteroids are not so well known to scientists or laypersons as are the planets and their larger satellites. Here we briefly describe some objects that are of particular interest as targets for early missions.

COMET HMP: Along with Encke and Tempel 2, Comet Honda-Mrkos-Pajdusakova is one of the brightest of the accessible, short period comets. It was discovered in 1948 independently by the Japanese amateur astronomer Minoru Honda and the Czech astronomers Ludmilla Pajdusakova and Antonin Mrkos. Returning to the Sun's neighborhood every 5.25 years, this comet has been studied during each of its six apparitions. Its elliptical orbit takes Comet HMP from just beyond Jupiter at its greatest distance from the Sun to inside the orbit of Venus at perihelion. The comet is active for about 20 days on either side of closest approach to the Sun, when it develops an atmosphere or coma of dust and gas 50,000 km across. At the same time, its ion tail can extend 500,000 km away from the Sun. Comet HMP could be studied at its 1995 apparition by both rendezvous and atomized sample return missions.

ASTEROID 4 VESTA: Vesta is the brightest minor planet and the third largest, with a diameter of 550 km. It was discovered in 1807 by Olbers in Breman, Germany, and under favorable circumstances it can just be seen with the naked eye. Probably among the best studied of all asteroids, Vesta is apparently unique among the larger objects in having a surface of basaltic lava, indicating a complex geological history of heating and volcanism. Many meteoriticists believe Vesta may be the parent body of the eucrite class of meteorites; although not proven, this theory is the most probable connection between specific meteorites and an asteroid parent body. Telescopic studies show that Vesta is nearly spherical, with several types of igneous rock on its surface. With its low orbital inclination, and distance from the Sun of 2.36 AU, Vesta is among the most easily reached of the large Mainbelt asteroids.

ASTEROID 19 FORTUNA: Even easier than Vesta as a target for rendezvous and orbit is Fortuna, a 200-km diameter asteroid discovered in 1852 by Hind in England. Fortuna is typical of the most populous class of asteroids, which are very dark and are thought to be composed of carbon-rich and volatile-rich materials similar to those of the carbonaceous classes of meteorites. Fortuna is therefore believed to be of very primitive composition, representative of the original condensates from the solar nebula between the orbits of Mars and Jupiter.

ASTEROID 433 EROS: Discovered in 1898 by Witt in Berlin, Eros is the largest of the class of Earth-approaching objects. Under favorable circumstances it passes only 0.13 AU (20 million km) from the Earth, at which time it is one of the brightest of the asteroids. Eros' surface is stony or stony-iron in composition. It is highly elongated, with probable dimensions of 18 × 36 km; it is even speculated that Eros may be two objects, orbiting in contact. At its 1989 apparition, Eros is an easy rendezvous target even with a relatively simple launch vehicle.

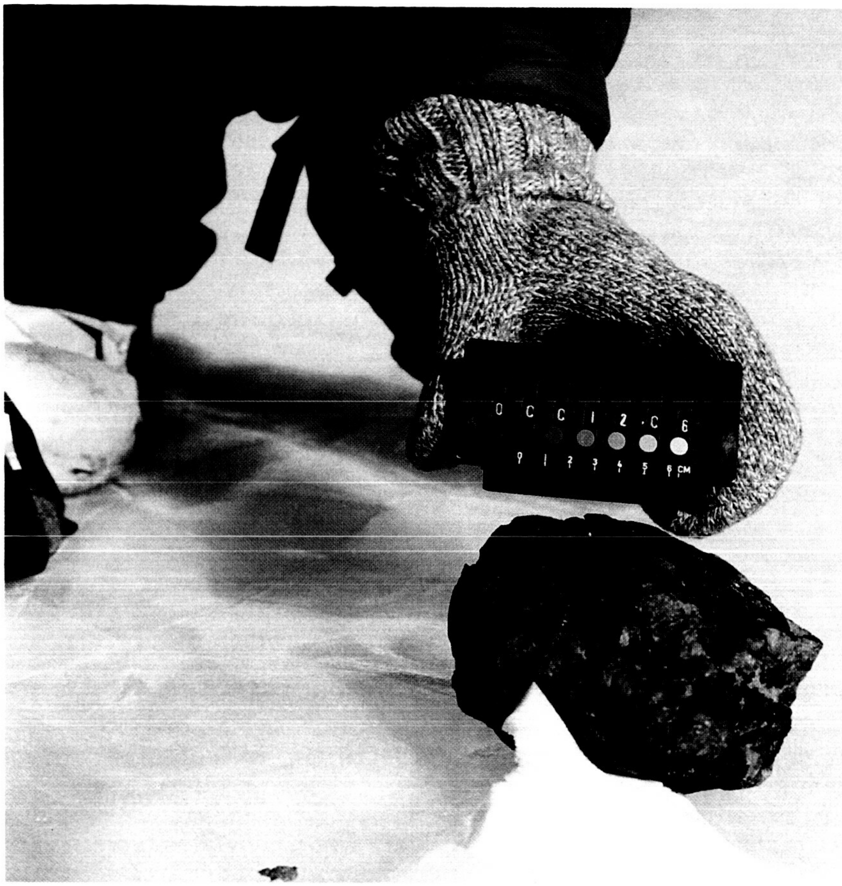
well to remember the great diversity already evident in the limited ground-based data. While some asteroids could turn out to be rather similar to small planetary satellites already studied, others are probably novel types of planets made of exotic materials like nickel-iron alloy, and still others may hold unique clues about the environments in which many of the larger planets—including our own—were born.

DEVELOPMENTS SINCE COMPLEX REPORT: The 1980 National Academy of Sciences' COMPLEX report on primitive solar-system bodies called the exploration of comets and asteroids "an essential element of a balanced program of solar-system exploration." A series of prioritized science objectives were developed by COMPLEX for both comets and asteroids. The cometary objectives focus on determining the composition and physical state of the cometary nucleus and on understanding the processes that govern the composition and behavior of the cometary atmosphere and solar wind interaction.

Studies of comets should consider several objects in different stages of evolution ("new" to nearly "dead"), as well as the changing evolution of a single comet during perihelion passage. The scientific goals for asteroids emphasize determining composition and also deal with surface morphology and evidence concerning internal properties. Both sets of science objectives highlight the investigation of the diversity of the two types of bodies. COMPLEX recommended studying a diversity of asteroids, including representatives of the common and unusual spectral classes, as well as bodies in a range of orbits and sizes.

From the perspective of 1982, the fundamental science goals for comets and asteroids remain essentially intact. There has been increasing interest during the last two years in the Earth-approaching asteroids, a population which may contain dead comet nuclei and fragments of Mainbelt asteroids. This increased interest derives from the scientific interests that relate asteroids to meteorites and terrestrial impacts, as well as from the more practical potential uses of these bodies. With the added emphasis on Earth-approachers, however, the Working Group reiterates the basic COMPLEX science goals and the chief arguments on which those goals were based.

IMPLEMENTATION STRATEGIES AND MISSIONS: The comets and asteroids remain unexplored after twenty years of planetary missions, in part because of uncertainties concerning the most effective mission modes for such small and numerous bodies. Some previous studies have concluded that adequate characterization of the required variety of comet and asteroid types would necessitate the development of new technologies such as low-thrust propulsion. An important element of the SSEC detailed study of small bodies has been the critical examination of the capabilities of several mission types, including rendezvous, orbiter, flyby, and atomized sample return. As a result of these studies and of newly identified mission opportunities that do not require low thrust propulsion, we conclude that we now have available the means to achieve the COMPLEX science goals in a practical, cost effective way.



This meteorite, which probably came from an asteroid, was found on the surface of the Reckling Ice Field in Antarctica. Meteoritic fragments from the Moon and possibly Mars also have been found within this nearly pristine environment.

RENDEZVOUS AND ORBITER MISSIONS: For both comets and asteroids, the most effective mission strategies require that the spacecraft spend a long time in the vicinity of the target. For comets and Earth-approaching objects, which have gravitational spheres of influence no more than a few tens of kilometers, we refer to rendezvous missions, while for the larger targets among the Mainbelt asteroids, the term orbiter seems more appropriate. These mission modes have been at the focus of previous studies, and were central to the recommendations made by COMPLEX (1980).

Only with a rendezvous is it possible (short of landing) to study a comet nucleus in any detail. And only with a rendezvous can the rapid evolution of cometary activity be investigated as the solar heating changes. In its 1979 report, the NASA Comet Science Working Group strongly endorsed a rendezvous with a short-period comet, such as Tempel 2 or Encke, as one of two essential elements in initial exploration of the comets. The other element, a fast flyby of Halley, will be accomplished in 1986 by European, Soviet and Japanese spacecraft. It now remains for the second step in this program to be carried out.

Except for some direct measurements required of the cometary gas and dust, instrumentation for rendezvous and orbiter spacecraft derives directly from experience with planetary remote sensing. A baseline payload for remote sensing of either an asteroid or a comet nucleus might consist of a CCD imaging system, an infrared reflectance

spectral mapper, and X-ray and gamma-ray spectrometers, The first two of these could be derivatives of *Galileo* instruments, while X-ray and gamma-ray techniques have advanced considerably since their successful use in the *Apollo* program. In addition, the comet rendezvous spacecraft should carry neutral and ion mass spectrometers for analysis of the gas in the cometary coma and a dust collector and analyzer to acquire, count, and determine the composition of the solid component of the coma. Of these, the dust analysis instrumentation is least well-developed, although a number of promising designs have been studied. Also, synergystic interaction between *in situ* dust analyses from the rendezvous spacecraft and laboratory studies of a returned atomized dust sample may influence strategy, perhaps including a de-emphasis of *in situ* analysis. Finally, these spacecraft would probably carry a magnetometer and could support other particles-and-field instruments if desired.

Rendezvous and orbiter missions have some particular advantages for small-body missions, beyond their capability of permitting the observation of evolving cometary activity. Several remote-sensing techniques, notably X-ray and gamma-ray spectrometry, require close proximity and long integration times to build up sufficient signal; these cannot be achieved during rapid flyby. Also, to thoroughly characterize the shape and geophysical configuration of a body, for example, to determine the volume (hence density) to high precision, it is necessary to observe the body from many different vantage points with high resolution. For very small bodies only a few kilometers in size or smaller, other simpler observations are also impaired by fast flyby due to the extremely brief duration of proximity to the body; therefore, rendezvous is especially important for studying comet nuclei and small Earth-approaching asteroids in contrast to the larger, Mainbelt asteroids, which can be studied fairly well during flyby.

FLYBY MISSIONS: Scientific advisory groups, including COMPLEX, have emphasized the great advantages of rendezvous or orbiter spacecraft over flyby missions. Clearly the long dwell times and varied perspectives obtainable from an orbiter, as well the capability of monitoring changes over time, address many science objectives not possible with a flyby. In particular, the long integration times needed to more fully determine composition by X-ray and gamma-ray remote sensing techniques are impossible during flyby. However, we believe that there remains an important role for flyby missions.

Flybys have three obvious advantages over orbiters for comet and asteroid exploration: 1) they permit us to reach otherwise dynamically inaccessible objects such as high inclination comets like Comet Halley; 2) they can be combined in a single mission to permit a sampling of the diversity inherent in such groups as the Mainbelt asteroids; and 3) they can often be accomplished with shorter trip times and shorter operational durations than orbiters. Such considerations argue strongly for flybys, to the degree that they are truly capable of addressing fundamental scientific questions.

In the case of the initial exploration of the asteroids, the importance of multi-target missions again draws our attention to flybys. Both COMPLEX and the 1978 NASA Asteroid Working Group placed great

A solar-powered spacecraft draws near a rendezvous with this typical asteroid (painting).

emphasis on the need to sample the diversity of asteroid types, but without an advanced solar electric propulsion system, multi-rendezvous missions (to more than two objects) are not possible. We have therefore examined the capabilities of flybys for the reconnaissance of the Mainbelt asteroids in particular.

Typical asteroidal targets are between 25 km and 500 km in diameter and will be encountered at relative velocities of a few km/sec. (Note that few target asteroids will be as small as Phobos, and some will be as large as the outer planet moons Amalthea, Hyperion, and Mimas). With optical navigation, flybys can be made almost arbitrarily close. If we assume remote-sensing instrumentation of the *Galileo* orbiter class, how well can the COMPLEX science objectives for asteroids be met?

The first objective is the determination of composition and bulk density. Masses can be measured to a few percent, and volumes to perhaps 10-15%, depending on the degree of surface irregularity. Densities should therefore be accurate to 10-20%, sufficient to provide significant constraints on bulk composition. Surface mineralogical composition can be inferred and mapped using a *Galileo*-type multi-spectral infrared imaging system. While no direct elemental or isotopic data can be obtained, the determination of surface mineralogy and bulk density would significantly address, for a diverse group of bodies, the highest-priority science issue. The compositional data would be superior to that now available for any solid solar system body except the Earth, the Moon, Venus, and Mars. Ground-based techniques will be surpassed, especially because the imaging mode will sort through the hemispherical averaging inherent in telescopic data. Mineralogical

assemblages which separate the major and minor classes of meteorites can be distinguished in most cases.

The second COMPLEX objective concerns surface morphology and geological processes. Flyby imaging should achieve global coverage at kilometer resolution, e.g., at resolutions equal to the best obtained by *Voyager* for the Galilean satellites, with 10-to-100 meter resolution over much of the encounter hemisphere. Such resolution and coverage is comparable to the objectives for Venus that were proposed for the *VOIR* radar mapper, and only slightly inferior to that obtained by *Viking* for Mars. It should permit detailed insight concerning the geophysical structure and geomorphology of types of bodies never before studied, including perhaps bodies of metallic composition. The use of flybys to study one or more members of Hirayama family—the presumed fragments of a disruptive collision—would permit the interior of the precursor body to be examined directly.

The third-priority COMPLEX objective for asteroids is the determination of the state of magnetization and of the interior. A flyby magnetometer can provide data on any global magnetic field.

In its report, COMPLEX emphasized the need to address significant aspects of objectives 1 and 2 in the same mission. We conclude that a flyby meets this criterion. The Working Group therefore considers that flyby encounters with small bodies can meet fundamental science goals, particularly for the larger Mainbelt asteroids which, because of their number and diversity, can never be fully explored by rendezvous/orbiter missions. The most effective exploration implementation mode that can be accomplished using present technology is a combination of rendezvous and flyby encounters using ballistic (i.e. not requiring low-thrust) propulsion techniques: opportunities have been identified where a spacecraft could make several flyby encounters with Mainbelt asteroids while in transit from one asteroid orbit encounter to another.

ATOMIZED SAMPLE RETURN FROM COMETS: Sample return missions can provide uniquely detailed information on solar system bodies because of the sensitivity, precision, and flexibility of modern laboratory analytical techniques. The productivity of the sample approach has been amply proven by the rewarding insights gained about the Moon and meteorite parent bodies from laboratory studies of extraterrestrial materials.

Due to difficulties in obtaining samples from most solar system bodies, it is usually assumed that sample returns can be attempted only after a sequence of reconnaissance and exploration missions. For comets, however, one kind of sample return can be considered for an early mission. Highly simplified techniques permit particles to be collected directly from the coma of a comet. The simplest method is by a high velocity flyby, as close to the nucleus as possible. The spacecraft would be launched on an Earth-return trajectory, and terrestrial recovery could be accomplished by placing the collected sample into a small atmospheric entry capsule similar to the *Discoverer* capsule used for film recovery from Earth orbit.

The flyby sample return is termed an ***atomized*** or ***plasmatized*** sample return because the particles are vaporized as they impact and

penetrate a thin diaphragm at velocities of 10-70 km/sec. The resulting vapor condenses on the walls of the cell in which it is then retained. The collector is compartmentalized so that material from individual particles can be analyzed separately in place using surface analysis techniques such as the ion microprobe. Alternatively the deposit can be dissolved from cell walls and mounted for analysis by focused beam X-ray fluorescence or solid source mass spectrometry.

Analysis may yield the elemental and isotopic composition of numerous particles, which should be a representative sample of coma solids at the time of encounter. Since such particles are freshly excavated from active regions of a comet, their composition should provide a good estimate of the non-volatile composition of a comet nucleus. Hundreds to thousands of particles, a few micrometers to a millimeter in size, could be collected. Even if the bulk composition determined from cumulative analysis of all the cells closely matches solar abundances, the individual analyses will enable a fundamental comparison with other primitive solar system materials. For example ordinary chondrites, and some carbonaceous chondrites and interplanetary dust, all have very similar bulk compositions, but are readily distinguished from each other by their fine-scale variations, which reflect important differences in their early processing. Nearly all major and minor elements and some trace elements can be measured to accuracies sufficient for meaningful comparison with the elemental fractionation patterns seen in chondrites. These comparisons include both the large variations in volatile elements and the smaller ones in siderophiles and refractories. In particular it is expected that abundances of Ca, Al, Ti, and Mg can be measured well enough to show any of the 10-40% fractionation effects seen in chondrite groups. Precise isotopic measurements are possible for some representative elements at accuracy levels where isotopic effects are seen in meteorites. For particles larger than 100 μm it will be possible to measure the Sr isotopic composition accurately enough to determine an Rb-Sr model age.

Coma sample return will provide a unique chance to compare meteoritic materials that come from unknown parent bodies with material released from a known comet. It is important that the sampled comet be well-characterized by complementary studies (both Earth-based and by spacecraft rendezvous), preferably including the time when the sample is collected. This simple collection technique is applicable to many comets, including those in highly inclined orbits, but it has limited scientific scope compared with the more complex and costly option of collecting pristine cometary samples that include the volatile component. We believe this simple collection approach has an important role in the early stages of spacecraft exploration of comets and is consistent with the limited-scope approach of the SSEC Core program.

SPECIAL CONSIDERATIONS FOR EARTH-APPROACHING ASTEROIDS: The Earth-approaching objects require a discussion separate from that for the comets and the Mainbelt asteroids. Unlike the Mainbelt asteroids, which are generally believed to remain near their positions of origin, the Earth-approachers are in unstable orbits and are being

replenished from elsewhere. Some may be fragments of disrupted Mainbelt asteroids, while others are probably dead comet nuclei. We do not know the relative importance of these two sources, nor can the provenance of individual bodies be ascertained. They may have a great deal to reveal about both comets and Mainbelt asteroids, and are almost certainly related to some meteorites.

Of the more than 1,000 Earth-approaching objects of kilometer size or larger believed to exist, only several dozen have been discovered. Even this small sample, however, includes several objects more accessible for Earth-return rendezvous missions than any other objects outside the Earth-Moon system. In fact, some are comparable to the Moon itself in ease of access. For this reason the Earth-approachers are prime candidates for manned exploration, if and when we choose to venture beyond the Moon. They are also an obvious resource for materials in space, and a great deal of attention has been directed to their potential role in large-scale in-orbit construction. For these reasons, interest in them far exceeds the purely scientific desire to explore a new population of solar system objects. Although human visits and use of space resources may seem far in the future, the fact is that we have hardly begun to assess the potential significance of these objects. A number of exploratory missions will be required to be able to judge their ultimate usefulness for the future of space travel and space industrialization.

Most Earth-approachers are small objects, much less than 10 km in diameter. The exploration of such objects can use the same rendezvous approach as used to study a comet nucleus. It should concentrate on detailed chemical analysis and high resolution imaging. Individually,

Microscopic, cosmic dust particles such as these, "fly-trapped" by high-flying U-2 research aircraft, provide clues to the origins of the solar system.

several of these objects are easy to reach, requiring modest launch vehicles and short transfer trajectories. At least one multiple rendezvous mission involving two Earth-approachers has been identified, but such mission opportunities are not thought to be common. Because these objects are so small, flybys are less useful than for larger Mainbelt asteroids. These considerations lead us to recommend use of simple spacecraft to rendezvous with at least one Earth-approacher. Short operation times would make this a particularly inexpensive mission.

RECOMMENDED MISSIONS: The potential significance of comets, Mainbelt asteroids, and Earth-approaching objects as contributors to our understanding of the origin and evolution of the solar system has been repeatedly stressed by science advisory groups and is summarized in the preceding sections of this chapter. It is clear that each of these categories contains a variety of interesting individual objects, and that exploration of each will contribute in different ways to our basic understanding of the planetary system and its genesis.

Confronted with these diverse and exciting targets for initial exploratory missions, we cannot rank comets versus asteroids versus Earth-approachers in terms of intrinsic scientific or intellectual value. To obtain a proper perspective on the solar system we must increase our understanding of each. Selection of specific missions, and of the order in which they should be initiated, must therefore be made on technological and programmatic grounds, with the overall objective of completing initial exploration of each group before the end of this century.

Following the flyby missions to Comet Halley in 1986, the next step in cometary exploration should clearly be a rendezvous with a short-period comet. A complementary approach to rendezvous is the acquistion and return to Earth of an atomized sample. The Working Group recommends that both of these missions, preferably directed toward the same comet, be in the SSEC Core program.

The Mainbelt asteroids require a combination of flybys and orbiters to achieve the depth and breadth necessary for an initial characterization. These can be achieved by one or two dedicated asteroid missions including orbits of at least two objects plus selected flybys, supported by asteroid flybys carried out by the comet rendezvous spacecraft and by outer planets missions (beginning with *Galileo* in 1987) en route to their primary targets. The Working Group recommends that this asteroid mission be in the SSEC Core program.

The Earth-approaching objects can be explored by rendezvous missions to one or more of them. Because it is not generally possible to include more than one target in the same mission (no case of more than two has been identified), we doubt that there is a single mission, such as exists for the Mainbelt asteroids, that can appropriately explore the diversity of these objects. Therefore, we recommend that a dedicated mission to one or more Earth-approaching objects be included within the Core program, but with lower priority than the comet and Mainbelt asteroid missions. We further point out that Earth-approachers are thought to be derived from both Mainbelt asteroids and/or short period comets; therefore, if the reconnaissance goals for comets and

Mainbelt asteroids are carried out before exploration of one or two Earth-approachers, we might have sufficient information to accomplish a more intensive study of the Earth-approachers on a first mission. We also note, in the context of the secondary goal of the SSEC to consider utilization of space resources, that early exploration of Earth approachers may be desired for other than purely scientific objectives. In that case, we believe that very significant scientific return could be achieved from such a mission, even if it were not to take advantage of earlier reconnaissance of asteroids and comets or were not to explore as wide a range of diversity.

The Working Group thus recommends a Core program of missions, with the comet and Mainbelt asteroid missions at top priority and the Earth-approaching asteroid mission with slightly lower priority. If the atomized plasma-return part of the comet mission cannot be accomplished for the ***same*** comet simultaneously with the rendezvous mission, and were flown to another comet, then it would have slightly lower scientific priority than either the comet rendezvous or asteroid missions. As part of a rendezvous with the same comet, atomized sample return has equal priority to the other two.

The Working Group thus recommends the following Core program of missions for the initial exploration of the small bodies (listed in temporal launch sequence; their priorities are as discussed above):

- *Short-Period Comet Rendezvous* (with *Mainbelt Asteroid Flyby)*
- *Mainbelt Asteroid Multiple Orbiter/Flyby*
- *Comet Atomized Sample Return* (preferably in association with rendezvous)
- *Earth-Approaching Asteroid Rendezvous*

To determine specific targets and launch opportunities for these missions, we must consider the problem of target selection.

TARGET SELECTION: Since there are so many possible targets, their selection is a critical element in planning a series of small bodies missions. For comets, we recognize that no large, highly active known target will be available after Halley for at least several decades. New comets (i.e. comets on their first passage through the inner solar system), are impractical because their orbits, even if one should prove suitable, are not known far enough in advance to launch a spacecraft on an intercept trajectory, at least as part of a cost-constrained program. Therefore we limit our consideration to the class of short-period comets.

Among the short-period comets, we have examined all launch opportunities during the rest of this decade to any of the half-dozen brightest objects in this category dynamically accessible. (Figure 10). The most desirable targets are the brightest (largest and most active): Encke, Tempel 2, and Honda-Mrkos-Pajdusakova (HMP). Among these, Encke is the most difficult from an engineering point of view because of its perihelion inside the orbit of Mercury. We have therefore focused attention on the other two, each of which provides excellent mission opportunities.

Figure 11 summarizes the opportunities for comet ballistic rendezvous missions during the 1990s based on the 600-kg *Mariner Mark II* spacecraft with a maximum in-orbit impulse of $\Delta V = 3.0$ km/sec, launched by either the *Shuttle/IUS* or *Shuttle/Centaur*. The outstanding opportunity is that presented for a 1990 launch to Comet HMP, which would yield the earliest practical rendezvous (1995) with either of the two highest-priority targets. However, it is important to note that an opportunity exists each year to launch a suitable comet mission with the *Shuttle/Centaur* combination.

Most of these rendezvous targets are also accessible to flyby/sample return missions that could return an atomized coma sample for analysis in terrestrial laboratories. In particular, Comet HMP could be reached in its 1995 apparition by a spacecraft launched in 1994 by the *Shuttle/IUS*, returning its sample to Earth in 1996. Figure 12 summarizes the opportunities identified for this class of mission.

Selection of targets among the Mainbelt asteroids is much easier, in the sense that there are a great many suitable objects, but more time-consuming in that multiple-asteroid missions are required. A detailed search for multi-asteroid missions has clearly shown that numerous orbiter plus multi-flyby and orbiter plus orbiter missions exist, and that these missions can be initiated at two-year intervals based on launch systems now under development (i.e. *Shuttle/IUS* and *Shuttle/Centaur)* using powered Mars flyby trajactories. (The potential for accomplishing some remote-sensing science at Mars should be noted.)

Figure 10: Candidate Comets for Rendezvous Missions

Comet	Mp	Period (Years)	Perihelion Distance (AU)	No. of Apparitions	Perihelion Passage	Ground-based Viewing
Encke	7.6	3.3	0.34	52	2000	Poor
Honda-Mrkos-Pajdusakova (HMP)	8.9	5.3	0.55	6	1995 2001	Excellent Poor
Tempel 2	9.5	5.3	1.38	17	1999 2005	Good Poor
Wild 2	9.7	6.2	1.49	2	1997	Good
Kopff	10.3	6.4	1.57	11	1996	Excellent
Churyumov-Gerasimenko (CG)	11.5	6.6	1.28	3	1996 2002	Excellent Fair

Figure 11: Comet Rendezvous Missions Opportunities

(Net Spacecraft Mass: 600 kg)

LAUNCH VEHICLE	MISSION CHARACTERISTICS	1990	1991	1992	1993	1994	1995	1996	1997
					LAUNCH YEAR				
STS/IUS	COMET	C-G		Temp 2	HMP	Encke	Kopf	C-G	Temp 2
2-Stage/	Perihelion Yr	1996		1999	2001	2000	2002	2002	2005
STAR-48	Traj. Mode	ΔVEGA		ΔVEGA	ΔVEGA	ΔVEGA	ΔVEGA	ΔVEGA	ΔVEGA
	Flight Time*	5.9 yr		6.9 yr	7.2 yr	6.4 yr	TBD	TBD	7.3 yr
	Total AV Req'd	3.0 km/s		2.7 km/s	2.9 km/s	2.7 km/s	TBD	TBD	2.8 km/s
	L.V. Margin	16%		26%	19%	26%	TBD	TBD	23%
STS/	COMET	HMP	Kopf	Wild 2	Temp 2	Temp 2	HMP	Encke	TBD
Centaur F	Perihelion Yr	1995	1996	1997	1999	1999	2001	2000	2001
	Traj. Mode	D	D	D	ΔVEGA	D	D	JGA	
	Flight Time*	5.0 yr	4.8 yr	4.2 yr*	5.9 yr	5.0 yr	5.3 yr	4.3 yr	
	Total AV Req'd	2.7 km/s	2.3 km/s	2.6 km/s	3.5 km/s	2.2 km/s	2.5 km/s	2.1 km/s	
	L.V. Margin	18%	34%	29%	42%	33%	23%	27%	

*Arrival 50 days before Comet Perihelion except for Wild 2 where arrival is 320 days before perihelion

The search for multi-asteroid opportunities was carried out for both the *Shuttle/IUS/Star-48* and the *Shuttle/Centaur F* combinations. The *Shuttle/Centaur* provides greatly improved performance, allowing increased flexibility in the selection of targets. At this writing the full range of opportunities during the 1990's has not been explored, and it is therefore premature to select a specific, optimum mission. However, Figure 13 illustrates several instructive examples for launches early in the decade of the 1990's, demonstrating our ability to carry out a variety of flyby/orbiter combinations that include several large and/or particularly interesting objects.

The most easily reached asteroids are those in the inner part of the belt (inside 2.5 AU) having small orbital inclination. These include asteroid 4 Vesta, which is not only one of the largest but also one of the most interesting compositionally, with an apparently basaltic surface, which indicates a past history of geochemical differentiation and surface volcanism. Even easier to reach is 19 Fortuna, an excellent example of the dark, volatile-rich asteroids that are thought to be chemically representative of the original condensates from the solar nebula between the orbits of Mars and Jupiter. Figure 13 lists several multi-asteroid missions that include orbiters of Vesta or Fortuna.

An important element of our total strategy for asteroid exploration is the exploitation of targets of opportunity presented when other spacecraft traverse the asteroid belt. As an example, the probable

Figure 12: Comet Flyby/Sample Return Mission Opportunities

(Net Spacecraft Mass: 600 kg plus kg for Return Capsule, Dust Shield, and Sample Collector)

MISSON					LAUNCH YEAR					
CHARACTERISTICS	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
COMET	HMP	BORR	T2	—	HMP	—	WILD 2	—	—	T2
Perihelion Yr	1990	1994	1994	—	1995	—	1997	—	—	1999
Flight Time	3 yr	4 yr	3 yr	—	2 yr	—	3 yr	—	—	3 yr
Encounter Time (Tp)	-15d	0	0	—	0	—	0	—	—	0
Flyby Speed - km/sec	14	18	11	—	12	—	10	—	—	11
Total ΔV - km/sec	0.2	0.2	0.8	—	0.2	—	0.7	—	—	0.3
L.V. Margin For 100 kg net S/C	20%	54%	40%	—	12%	—	39%	—	—	55%

*Launch Vehicle: *STS/IUS* 2-Stage/*Star-48*

trajectory to Jupiter for the *Galileo* spacecraft will permit close flybys of either 1219 Britta or 1972 Yi Xing. A preliminary search of the trajectory of the recommended 1990 launch for a rendezvous with Comet HMP has identified opportunities to fly by either 168 Sibylla (diameter 150 km) or 1295 Deflotte (diameter 50 km) in the first year after launch.

Earth-approaching objects are in a separate class because of the generally low requirements they place on launch vehicles. However, a search carried out for the known Earth-approachers indicates that multi-rendezvous, or even flyby-rendezvous combinations, are rare. The single-object rendezvous missions available during the rest of the century (Figure 14) include objects of several compositional classes and one special object, 433 Eros, which is by far the largest Earth-approaching object and may be similar to asteroids from the inner part of the Mainbelt.

A rare opportunity to rendezvous with two near-Earth asteroids in a single mission has been identified following the discovery in 1982 of a particularly favorable target, asteroid 1982DB. This mission involves a 1989 launch, a 3-month rendezvous with 1982DB in 1991, and a rendezvous with asteroid 1980AA in 1994. It is to be expected that discovery of other Earth-approachers (of which as many as a thousand are estimated to exist) will increase the opportunities for such multi-object missions, and the continuation of search programs for these objects is strongly endorsed by the Working Group.

Figure 13: Representative Mainbelt Multi-Asteroid Orbiter/Flyby Mission Opportunities 1990-92

(Based on *Shuttle/Centaur* and *Mariner Mark II*)

Launch Year	Asteroid	Type	Diam. (km)	Flight time (yr)	Stay time (d)	Payload Margin
1990	19 Fortuna	C	200	1.5	60	19%
	263 Dresda	U	40	3.5	60+	
1990	312 Pierrestta	S	50	1.2	flyby	52%
	19 Fortuna	C	200	1.7	60+	
1990	207 Hedda	C	60	1.0	flyby	57%
	113 Amalthea	U	50	2.7	flyby	
	27 Euterpe	S	120	4.6	212	
	136 Austria	?	40	8.2	flyby	
	751 Fiana	C	110	8.9	flyby	
1990	20 Massalia	S	140	6.3	99	44%
	44 Nysa	E	70	7.3	60+	
1992	4 Vesta	U	580	2.8	60	12%
	313 Chaldaea	C	120	4.1	flyby	
	101 Helena	S	70	5.1	flyby	
1992	4 Vesta	U	580	2.8	60	21%
	17 Thetis	S	100	3.8	flyby	
	101 Helena	S	70	4.4	flyby	

Figure 14: Near-Earth Asteroids Rendezvous Mission Opportunities

(Net Spacecraft Mass: 600 kg)

LAUNCH VEHICLE	MISSION CHARACTERISTICS	LAUNCH YEAR 1988	1989	1990	1991	1992	1993	1994	1997	1996
STS/IUS	ASTEROID			Anteros	1982 DB	Anteros		1980 PA		
2-stage	Rendezvous Yr			1992	1992	1993		1996		
	Flight Time			1.92 yr		1.58 yr	1.40 yr		1.80 yr	
	C_3 (km^2/s^2)			35.1	23.4	31.8		27.4		
	Total Post Launch ΔV		1.34	0.57	1.13		1.86			
	L.V. Margin			21%	59.8%	35%		22%		
STS/IUS	ASTEROID	Anza	Eros				Ivar		Anteros	Eros
2-Stage/	Rendezvous Yr	1991	1990				1995		1997	1997
Star-48	Flight Time	2.44 yr	1.89 yr				2.10 yr		2.00 yr	1.91 yr
	C_3 (km^2/s^2)	47.0	40.1				44.4		41.0	40.8
	Total Post-Launch ΔV	1.36	1.95				1.50		1.58	1.89
	L.V. Margin	38%	30%				37%		39%	31%

NOTES: 1. Data are for one-day launch periods except for Eros 1989 launch, which is for a 10-day launch period.
2. Total ΔV is the total of all post-launch ΔV and 0.115 km/s navigation and post-rendezvous maneuvers.
3. One mission for each year selected—alternates available for both launch vehicles.

Summary of Recommended Missions

RENDEZVOUS WITH SHORT-PERIOD COMET

- First Priority
- Launch early 1990's/Rendezvous mid 1990's
- *Mariner Mark II*
- *Shuttle-Centaur* launch vehicle
- Mainbelt asteroid flyby en route

MAINBELT ASTEROID ORBITER AND FLYBY

- Launch 1990-1994
- *Mariner Mark II*
- *Shuttle-Centaur* launch vehicle
- Orbiter at prime target (e.g. Vesta or Fortuna)
- Additional flybys of two or more compositionally different asteroids

ATOMIZED SAMPLE RETURN FROM SHORT PERIOD COMET

- *Mariner Mark II* or *Planetary Observer*, plus return capsule
- *Shuttle-IUS* or *Shuttle-Centaur* launch vehicle
- Encounter after one year trip, Earth return one year later
- Coma sample returned for laboratory analysis
- Complements science of rendezvous mission

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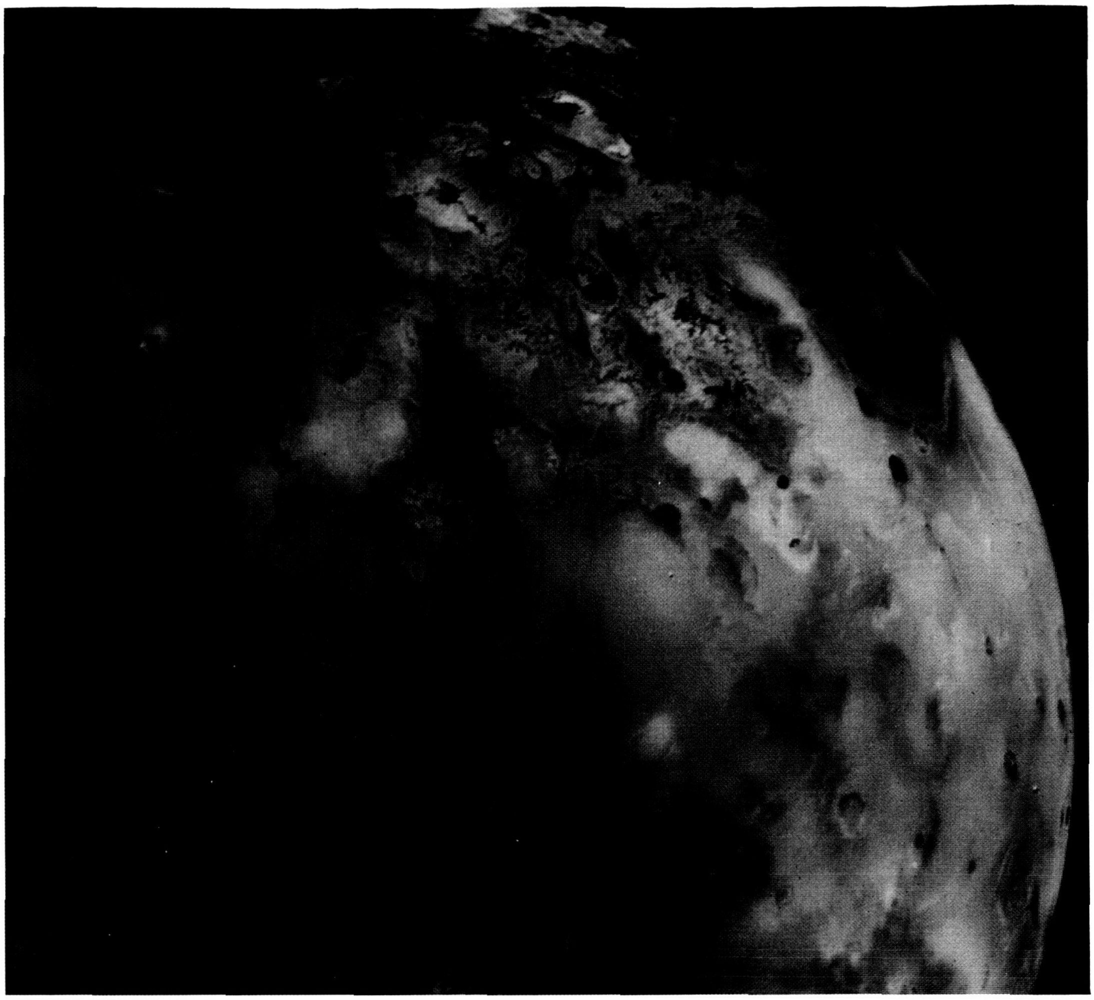
RENDEZVOUS WITH EARTH-APPROACHING ASTEROID

- *Planetary Observer*
- *Shuttle-PAM-A* equivalent launch vehicle
- Trip time under one year
- Instrumentation similar to inner planets geoscience orbiter plus imaging
- Addresses both science and resource goals

One of Voyager's *fascinating discoveries was active, sulfur-spewing volcanoes on Jupiter's moon, Io.*



Outer Planets

SCIENTIFIC BACKGROUND: To a visitor from some other part of the galaxy, the massive outer planets with their magnetospheres and systems of rings and satellites would seem almost to be the solar system. Excluding the Sun, these planets contain 99.6% of the system's mass, they have 45 of the 48 known satellites, the only ring systems, and in the case of Jupiter and Saturn, magnetospheres that are vastly larger and more complex than those associated with the inner planets.

Indeed, the outer planets are strikingly different from Earth and its nearest neighbors. The big four are mainly made of hydrogen, thereby exhibiting a close kinship with the Sun and stars. All except Uranus radiate more energy than they receive from the Sun, a consequence of internal, non-nuclear sources of energy. The colored clouds of Jupiter provide evidence for an atmospheric chemistry that is localized both vertically and horizontally. The reasons for this isolation remain elusive. Pluto is the only one of the outer planets with a well-defined solid surface. It is clearly different from its larger brethren; its small size and low density make it similar to one of the large icy satellites,

such as Titan. Pluto's own moon is unique in being larger in mass relative to Pluto than any other satellite relative to its planet, making Pluto virtually a double planet.

The other satellites in the outer solar system make up an extremely diverse collection. They include firey Io, the most geologically active body in the solar system, with at least 12 volcanoes in full eruption during the *Voyager* encounters; smooth Europa and icy Enceladus, whose surfaces are strongly modified by recent internal activity; Ganymede with its surface expression of a complex tectonic evolution, and Iapetus with one hemisphere totally coated with a very dark, presumably carbon-rich material. Also unique is Titan, with an evolved reducing atmosphere containing more nitrogen than our own in addition to methane, carbon monoxide, and a variety of other compounds. We may hope to study chemical processes on Titan today that are analogous to those that led to the origin of life on Earth. The surface of Titan is cold enough for methane to condense, opening the prospect that this satellite may be covered with pools, lakes, or even oceans of what we commonly call natural gas. The smaller icy satellites of Saturn seem likely to be related to comet nuclei, with objects like Phoebe and Chiron as possible intermediaries.

The magnetosphere of Jupiter is larger than the Sun. It contains protons and electrons with energies up to several million electron volts and is particularly remarkable for the torus of atoms, ions, and sub-atomic particles associated with the orbit of Io. Saturn's magnetosphere is smaller but replete with is own set of unusual characteristics. Both of these giant planets exhibit auroras as a result of the dumping of charged particles from their magnetospheres into the polar regions of their atmospheres. Interactions between the plasmas and the solids found within the magenetospheres are also in evidence, including sputtering on satellite surfaces and charging of small particles in the ring systems. The recent discovery of auroral activity on Uranus suggests that this planet also may have a magnetosphere. If so, it will be remarkable indeed, since the planet's rotation axis is practically in the plane of its orbit, a unique characteristic in our solar system. The difference in geometry plus the difference in bulk structure and composition of Uranus provides a new test of our ideas about the generation and maintenance of planetary magnetic fields.

In fact, we still know very little about Uranus, Neptune and Pluto since they are very distant planets and no spacecraft has visited them. But we already know that these objects are very different from one another and from Jupiter and Saturn. The meteorology on Uranus will be affected by the high inclination of the rotation axis. On Neptune we already have some evidence for the condensation of clouds on a global scale in periods of days. But we do not yet know the composition of these clouds.

This brief summary has emphasized the difference in scale and composition as well as the diversity of natural phenomena in the outer solar system compared with the inner planets. The underlying characteristic that unifies these different qualities is their primitive nature. We ourselves dwell on a cosmic cinder where the light elements that dominate the composition of the universe are severely depleted. The early history of the Earth is hidden from us as a result of natural

processes ranging from erosion and plate tectonics to the activities of living organisms. Some of the most important questions we would like to ask, such as those involving the origin of life and the origin of the solar system, simply cannot be answered if we confine ourselves to our own planet or even the inner solar system.

In giant Jupiter we have an opportunity to sample a reservoir of material unmodified by nuclear reactions or the escape of light elements since the solar system formed. We do not yet know whether the elemental abundances on Jupiter exactly match those on the Sun; the most recent work on this problem suggests that the heavy elements were somewhat enriched during formation of the planet. But Jupiter does seem to offer an atmosphere of hydrogen and helium in solar proportions, implying that the atoms of hydrogen, deuterium, and helium found there represent the relative abundances of these species as they existed in one part of the interstellar medium of our galaxy 4.6 billion years ago. We can then use these abundances with models of galactic evolution to determine the primordial abundances, thereby providing a sensitive test of the standard Big-Bang model for the origin of the universe. This jump to cosmology cannot be made in the inner solar system, where the light element abundances are hopelessly disturbed (even the Sun does not help since solar deuterium has been destroyed by nuclear burning).

To solve this problem rigorously in the outer solar system, we must know more about the formation of the planets—in itself a valuable exercise since it will tell us about the differentiation of matter in the solar nebula at large distances from the Sun. If we are to understand star formation fully, we must know how solar systems form. Ours is the only such system we know of at present, and certainly the only one we can hope to study in detail. The evolution of the solar nebula from a cloud of matter in the interstellar medium to the solar system we find today cannot be traced without explaining the most massive planets, accounting for their differences from each other as well as from their tiny cousins in the inner solar system. In the process we should learn more about just how homogeneous the nebula really was, not simply in terms of the small-scale structures represented by meteorites, but planet by planet. We can do this by measuring the atmospheric composition of each outer planet and using these results to calibrate both the observational data we already have (e.g., the abundance ratios of noble gases in meteorites and in the atmospheres of the inner planets). Despite the remarkable advances made by remote sensing, it is clear that we cannot hope to obtain data of the scope and precision we need without sending probes into the atmospheres of these bodies. Only in this way can we measure abundances of noble gases, isotope ratios of the volatile elements, and pursue the identification of the complex organic compounds produced from the simpler molecules our spectrographs have revealed.

Results obtained from such measurements can also be used to develop and to test models for the internal structure of the outer planets and their satellites. Such models rely on basic measurements of mass, figure, rotation rate, and gravitational moments. These quantities are more uncertain the greater the distance of the planet from the Sun. The gravitational moments are particularly difficult to

determine, but we still do not even have precise values for the rotation rates of Uranus, Neptune and Pluto.

The satellites of the outer planets offer an opportunity to study a great variety of solid planetary objects, with compositions ranging from silicate-rich Io and Europa to bodies rich in frozen volatiles like Ganymede, Callisto and the Saturnian satellites, and the possibly carbonaceous or chondritic composition of the very dark Uranian satellites. Satellite compositions and characteristics reflect not only early nebular temperature and pressure conditions but also give insight into the local modifications of nebula by the primary planet. The substantial thermal and geologic evolution of many of the satellites allows us to study planetary processes and tectonics under very different conditions from those in the terrestrial planets. Comparative study of the major satellite systems should also give us additional insight into many aspects of planetary system formation in general.

Only the outer planets have rings, and each ring system is different. Their unexpected diversity dramatically illustrates the importance of *in situ* studies. The Uranian ring particles, for instance, are extremely dark, while the Saturn ring particles are bright and icy. Rings are systems of colliding fragments similar to those that existed prior to the formation of satellites and planets. The physics of such systems is enormously complex. In the Saturn system, *Voyager* observations revealed spiral waves of density that are generated by satellites. These waves may transfer material great distances. Such waves were first postulated to explain the spiral structure of galaxies. Hence, the physics being developed to understand Saturn's ring system will clearly have application to many other astrophysical problems involving disks, including theories for the accretion of the Earth and the other planets. The relationship of rings to their "sheperding" satellites, and the evolution of discrete structures within a given ring are two examples of phenomena that may well have direct parallels in the early stages of planetary accretion.

Space missions are essential if we are to obtain the detailed information required to address these problems. This is even more true in the case of magnetospheres where flybys and orbiters provide the only ways to distinguish such characteristic features as bow shocks and variations in magnetic field strength. The study of these systems allows us to investigate *in situ* the behavior of plasmas, their interactions with fields and solid material, high energy trapped particles, and fundamental acceleration and source and sink mechanisms—all in systems of astrophysical scale.

The Saturnian magnetosphere is much like that of the Earth, very different from that of Jupiter. The Uranian magnetosphere, owing to the present orientation of the pole (pointing into the solar wind), is likely to be extremely unusual and to provide particularly useful constraints on magnetohydrodynamic theories. Such studies again give us a natural laboratory, in this case to study the complex interactions of matter and electromagnetic forces which are vital to understanding processes active throughout the universe. It seems fair to say that the *Pioneer* and *Voyager* spacecraft encounters with Jupiter and Saturn have virtually created new scientific disciplines associated

with the wealth of detail developed on the ring systems and magnetospheres of these giant planets.

DEVELOPMENTS SINCE COMPLEX REPORT: Although the work of the Outer Planets Working Group was made more complicated by the lack of an up-to-date COMPLEX science strategy for the outer planets (the current stategy dates from 1975 and is being revised in the light of the *Voyager* results and the discoveries made using telescopic techniques, e.g., the discovery of the Uranian rings), the Working Group found that it was readily able to establish mission priorities for future outer planet exploration. As we have seen, the giant outer planets offer us opportunities to investigate questions in cosmology, the origin of the solar system, the interactions of magnetic fields, charged particles and solids, the origin and dynamics of ring systems, and the origin of life itself in ways that we cannot achieve by studying the other members of the solar system. The task is to identify the missions that will achieve these goals.

Three key factors helped to guide the deliberations of the Working Group. First, it was concluded that additional missions to Jupiter during the time period in question do not have high priority because the *Galileo* mission will address the most important scientific goals identified by COMPLEX in its 1975 report, goals that remain equally valid in this post-*Voyager/Jupiter* era. Thus, further consideration of the Jupiter system was set aside (though, in a more expansionary climate, technologically challenging missions—for example, deep planetary probes and satellite landers—would become serious candidates to follow up the *Voyager* and *Galileo* discoveries).

The second key consideration was the heightened interest in the Saturnian system that has followed upon the *Voyager* flybys. Many important discoveries made by *Voyager* at Saturn lend themselves to further investigation using already developed techniques. Of these discoveries, those concerned with the giant moon Titan, the dark material on the leading hemisphere of Iapetus, and the complex Saturnian ring system, are considered to be of highest priority for follow-up in the next phase of Saturn-system exploration.

Titan, the largest satellite of Saturn, is unique in having a dense atmosphere, dominantly nitrogen but containing a small amount of methane and possibly argon. The surface pressure is 1.6 bars; with a gravity of 135 cm s^{-2} the amount of gas per unit area is nearly 11 times that on the Earth. A nearly uniform orange haze hides the surface and any clouds (most likely of methane) that might exist. Titan might seem similar to the terrestrial planets, but it is much colder and much richer in ices (mostly water ice that has trapped some methane and other gases). The surface temperature is 95°K, globally uniform rather like Venus, and a few degrees above the melting point of methane. There is a minimum of 70°K at an altitude of 40 km; the temperature in the stratosphere rises to 170°K at 200 km.

The circulation of Titan's atmosphere has only been studied theoretically. No features that could serve as tracers for wind velocities were observed in the ubiquitous haze. The variation in the reflectivity of the haze across the satellite's equator suggests a slow, seasonal circulation pattern, out of phase with the true seasons owing to the

long response time of the atmosphere. Both its period of rotation and the thickness of its atmosphere place Titan in an intermediate position between Earth and Venus. Thus, it offers a new and different set of parameters to test the general circulation models.

Strong absorption bands of methane were discovered in Titan's spectrum in 1944. Photochemistry initiated by ultraviolet absorption and electron bombardment gives rise to heavier hydrocarbons, nitriles, and other organic compounds, about ten of which have been identified so far. The hydrogen escapes rather rapidly, contributing to a flattened cloud around Saturn. The orange haze is undoubtedly composed of condensed organic compounds, among which polyacetylenes and cyanide polymers are likely to be important. There must be a deep layer (up to a half kilometer) of these materials lying on the surface or dissolved in any liquid methane that may be present. The atmospheric methane must be continuously replenished either from such lakes or seas or by episodic degassing from subsurface regions. Dense methane clouds are a possibility, but evidence for or against them is very indirect.

All the organic compounds on Titan can plausibly be derived by photochemistry of a nitrogen-methane mixture. Traces of CO and CO_2 are a different matter; indeed, they are the only forms of oxygen that are actually observed. The CO could be degassing from the interior, or could be formed from the ice in incoming meteoritic material, with the carbon coming from the atmospheric methane. The CO_2 must be in a photochemically steady state with the CO, via reactions with OH.

Inevitably there are many intriguing open questions about Titan at this point in our exploration of that body. For example, is argon really abundant? (if so, it demonstrates the formation of clathrate hydrates in the outer solar system). What is the composition of the aerosol? What are the abundances of important biological precursor molecules? Are there methane oceans, lakes, or clouds? Are there islands or continents, and if so, are they water ice or something else? Did N_2 come from NH_3 photolysis or was it primordial (related to argon and CO questions)? Is CO generated from infalling meteoroids or was it primordial? Is there structure in the temperature profile between 200 and 1,500 km, and what governs this profile? Are the predicted strong zonal winds (less than 100 m/s in the stratosphere) present? What other energy source in addition to the incident solar radiation causes the ultraviolet dayglow to be brighter (by a factor of 4) than the solar radiation can account for, and what confines it to the day side? Is there a small internal magnetic field? How does the co-rotating plasma interact with the upper atmosphere or magnetic field, and in what ways are the plasma and the atmosphere affected?

Many of these questions can be answered by a simple atmospheric probe of Titan, accompanied by a remote-sensing flyby spacecraft or a separate Saturn orbiting spacecraft. These missions therefore have very high priority.

Prior to *Voyager*, the extraordinary beauty and complexity of the Saturnian rings and their dynamics were unsuspected. Despite the *Voyager* discoveries, there are many important unknowns. Uranus and Neptune will no doubt provide further surprises. Much of the ring

dynamics may be time variable; in fact, theoretical timescales for ring evolution, even with observational confirmation of ring energies, are embarrasingly short. Many variable features were insufficiently observed by *Voyager* to characterize, most notorious of these is the puzzling, "braided" F-ring. Also, insufficient coverage was obtained to provide a meaningful search for possibly primordial "moonlets" embedded in the rings.

Much information lies in the variation of particle brightness and size between and within the different ring regions. The otherwise highly successful *Voyager* radio occultation experiment was severely handicapped and nearly "blind" in the most dense areas of the rings because of its highly grazing transmission angle. This has left us in ignorance as to the particle size in the main part of the ring. Unsuspected evidence was obtained that particles in certain regions are much darker than in other regions. Whether these differences imply differences in composition is a tantilizing question. The composition of the rings will provide an important constraint on the conditions in the vicinity of the forming planet and in the nearby protoplanetary nebula, as little if any metamorphosis has occurred in these icy particles. Experiments constraining the particle size and composition, including the distribution of fine dust in the system, could be implemented by even a flyby probe carrier. Electromagnetic effects associated with the rings—apparently including lightning-like bursts of radio static—continue to intrigue researchers. These phenomena could be investigated with a flyby or during the approach phase of an atmospheric probe.

Fully satisfactory studies of the ring structure and particle properties will call for the extended observational capabilities of an orbiting spacecraft. Stellar occultations could be used to characterize ring structure on the crucial 0.1-10 km radial scale, and allow azimuthal variations to be determined. Radar occultations may finally answer the continuing question of the vertical structure of the rings. Extended imaging observations can determine the distribution of embedded "moonlets" in the various empty gaps. The long time-base afforded by an orbiter mission will allow studies of the evolution of structure observed in individual rings. Such extended observations will also be needed to probe the complex time-varying Saturnian magnetosphere.

Even lacking the *Voyager* data, the high priority of the Saturn system for comparative studies would be obvious. The *in situ* determination of the composition and structure of Saturn's atmosphere will provide the basis for the systematic study of the giant planets. The *Voyager* data have already demonstrated that the hydrogen to helium ratio in Saturn's atmosphere is significantly higher than the value found on Jupiter. This result can be understood in terms of a model that predicts precipitation of liquid helium deep in Saturn's interior. The precise value of the ratio is important to test the theory. A comparison of the abundances of other species and their isotopic ratios with the same set of data to be obtained for Jupiter by *Galileo* would permit a large advance in our efforts to understand the differences between these two giant planets and to test for large scale variation in the composition of the primordial solar nebula. The outer planets are unique in

allowing us to gain a relatively deep understanding of their bulk composition by sampling their atmospheres. Such data are also needed from Uranus and Neptune to complete the picture.

Comparative studies of the Pluto system and the satellites of Saturn, Uranus and Neptune also are accorded high priority. The Saturnian moons were not observed as closely by *Voyager* as the large satellites of Jupiter and, in any case, they are smaller and in a different compositional class. Apart from Titan, these moons are too small for us to have predicted complex evolutionary histories, yet both Enceladus and Iapetus exhibit surfaces that have been drastically modified since the satellites were formed. It seems likely that the same internal activity that led to the obliteration of craters produced the particles that form the E-ring and maintain the uniquely high brightness of Enceladus' surface. But what is this activity? The reasons for the factor of ten difference in the reflectivities of the leading and trailing hemispheres* of Iapetus remain obscure after *Voyager*. With a maximum resolution of only 17 km, the *Voyager* pictures are too poor to allow a distinction between endogenic and exogenic processes. The nature of the dark material coating the leading hemisphere is also unknown. It does not have the same color as the surface of Phoebe, but its reflectivity does resemble that of the organic compounds extracted from a carbonaceous meteorite. This similarity, as well as the low albedo of approximately five percent, suggest that the dark hemisphere is coated with carbon-rich organic matter. Where did this material originate? Why does only one satellite in the solar system exhibit this bizarre asymmetry? What clues can this satellite give us that would help reveal the relationships of comets, icy satellites, the most primitive carbonaceous meteorites, and the role played by small bodies in the delivery of organic material to the surface of the primitive Earth? A long-standing puzzle in meteoritics has been the mode of origin of the organic matter found in carbonaceous chondrites. The dark surface of Iapetus may constitute a low-temperature reservoir of the precursors of the materials found in the meteorites.

We only know that the satellites of Uranus are small and dark, while Pluto and Triton—Neptune's largest moon—are known to possess an atmosphere containing methane. Comparative studies of these objects must be carried out to understand their differences and how they relate to the deeper problems of planet formation and early bombardment histories throughout the solar system.

The third factor that helped shape the Working Group's recommended mission strategy was the appreciation that the desired result of outer planet exploration in the period of interest is to bring studies of the other outer planets to the same high level that will be achieved by *Galileo* at Jupiter. Although the launch energy requirements increase as a function of planetary distance from the Sun, the technology needed to achieve atmospheric entry becomes less demanding and the required remote sensing techniques are similar. Therefore, the Working Group concluded that the technology developed for the *Galileo* mission could readily form the basis for the exploration of Saturn, Uranus and Neptune, a basis which, through high inheritance, should be affordable despite the long trip times.

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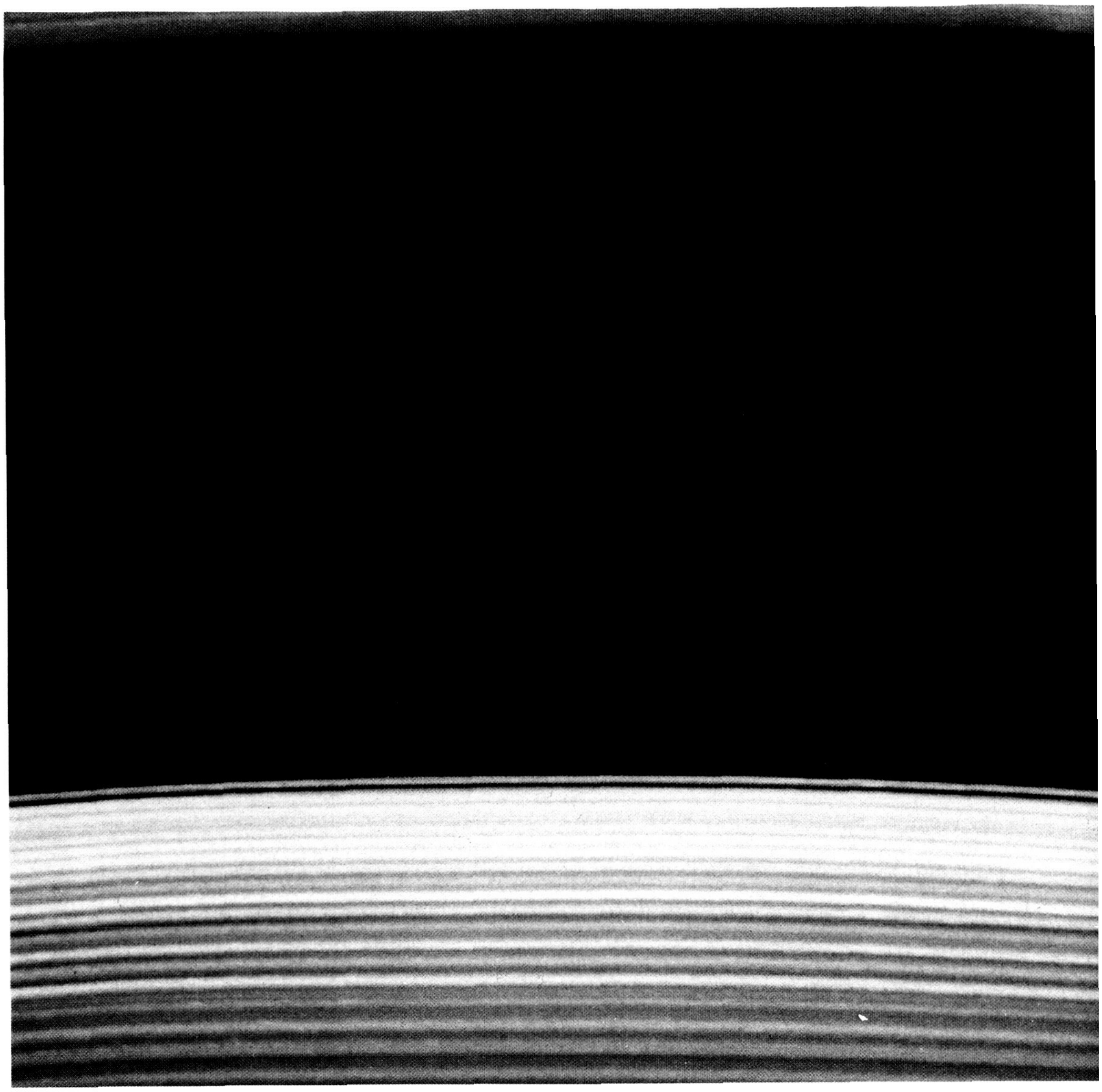
* The spin rates of the outer planet moons are, like our own Moon, synchronous with their orbital motions about the primary planet. Accordingly, one hemisphere always points in the direction of the orbital motion while the opposite hemisphere "trails."

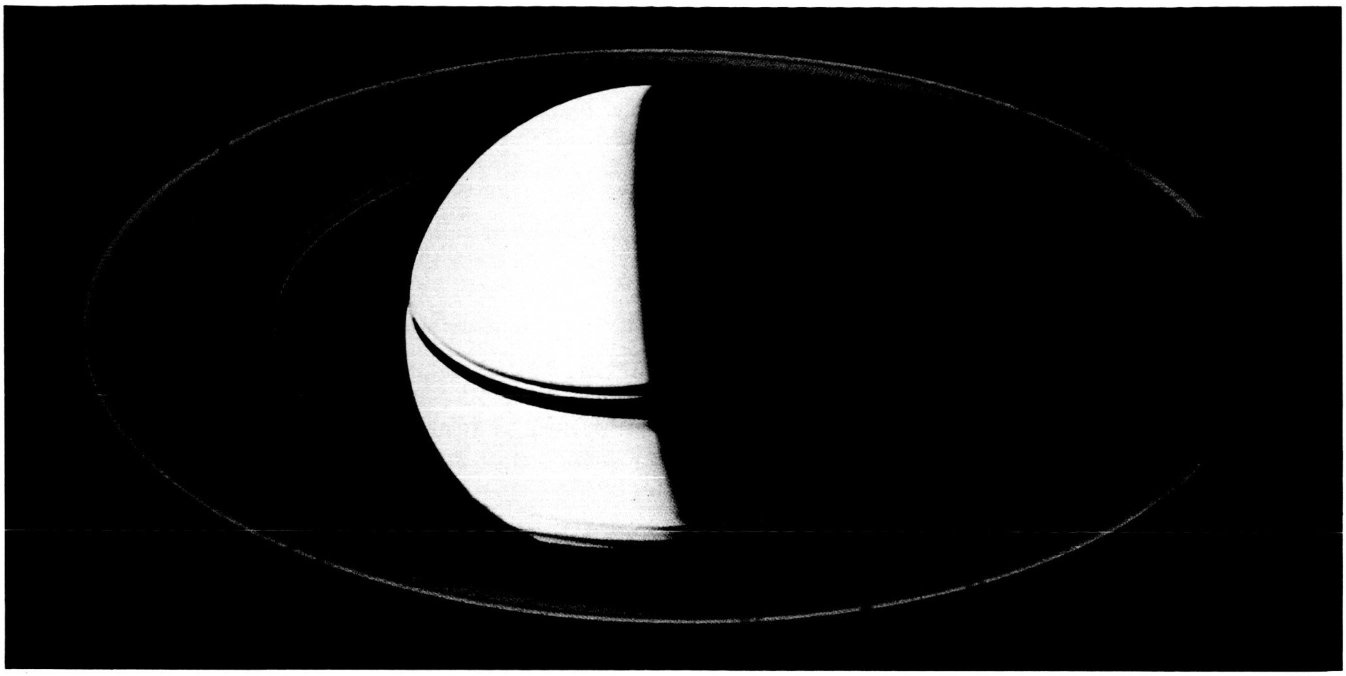
Voyager 2's *photopolarimeter obtained highly detailed images of the Encke Division in Saturn's outer A-ring.*



Given *Shuttle-Centaur* launch capability, orbiter missions beyond Saturn appear to be only marginally possible; the Working Group therefore assumed that, rather than orbiter and probe missions to Uranus and Neptune, only flyby/probe missions would be practicable. However, mission studies by NASA and by aerospace contractors show that flyby/probe missions are not only scientifically rewarding but also technically feasible with existing capabilities.

A special problem arises in the case of Neptune and Pluto. To achieve trip-times that are less than 10 years, it is necessary to use a Jupiter swingby to supply additional momentum to the spacecraft. These opportunities occur every 12 years, and the next set occurs in the early 1990's. To be ready for this opportunity, new starts for Neptune and Pluto missions must be initiated in a time-frame that would force them to compete with other SSEC priorities. The next opportunities occur early in the next century. That timetable

Four-and-one-half days after its closest approach to Saturn* Voyager 2 *cameras looked back to acquire this departure shot.



suggests that funding for a Pluto mission should be initiated in the period 1996-1998. A properly instrumented flyby mission to provide reconnaissance of this planet would finally bring Pluto in from the cold unknown and thereby achieve a significant milestone in the exploration of the solar system.

RECOMMENDED MISSIONS: The Working Group, on the basis of the considerations outlined above, established the following priorities for outer planet missions within constrained budget levels:

- *Titan Flyby/Probe*
- *Saturn Orbiter*
- *Saturn Flyby/Probe*
- *Uranus Flyby/Probe*
- *Neptune Flyby/Probe*
- *Pluto Reconnaissance Flyby*

The ordering of these priorities reflects the Working Group's efforts to blend together scientific interest, launch opportunities, and the desire for a balanced program of solar system exploration. Thus, the ordering should not be considered an inflexible judgment based strictly on scientific considerations. We can expect much new knowledge about all of these objects by the end of this decade, from the *Voyager* encounters with Uranus and Neptune, the use of the *Space Telescope,* and the continued application of ever more sophisticated ground-based techniques. These new results—as well as technological breakthroughs in the design of the missions themselves—could well cause us to change the order given above. To indicate the complexities in these choices, the first two missions might evolve into a Saturn orbiter with Titan probe, a mission currently under joint study by ESA and NASA, that would then be followed by a Saturn or Uranus probe. At

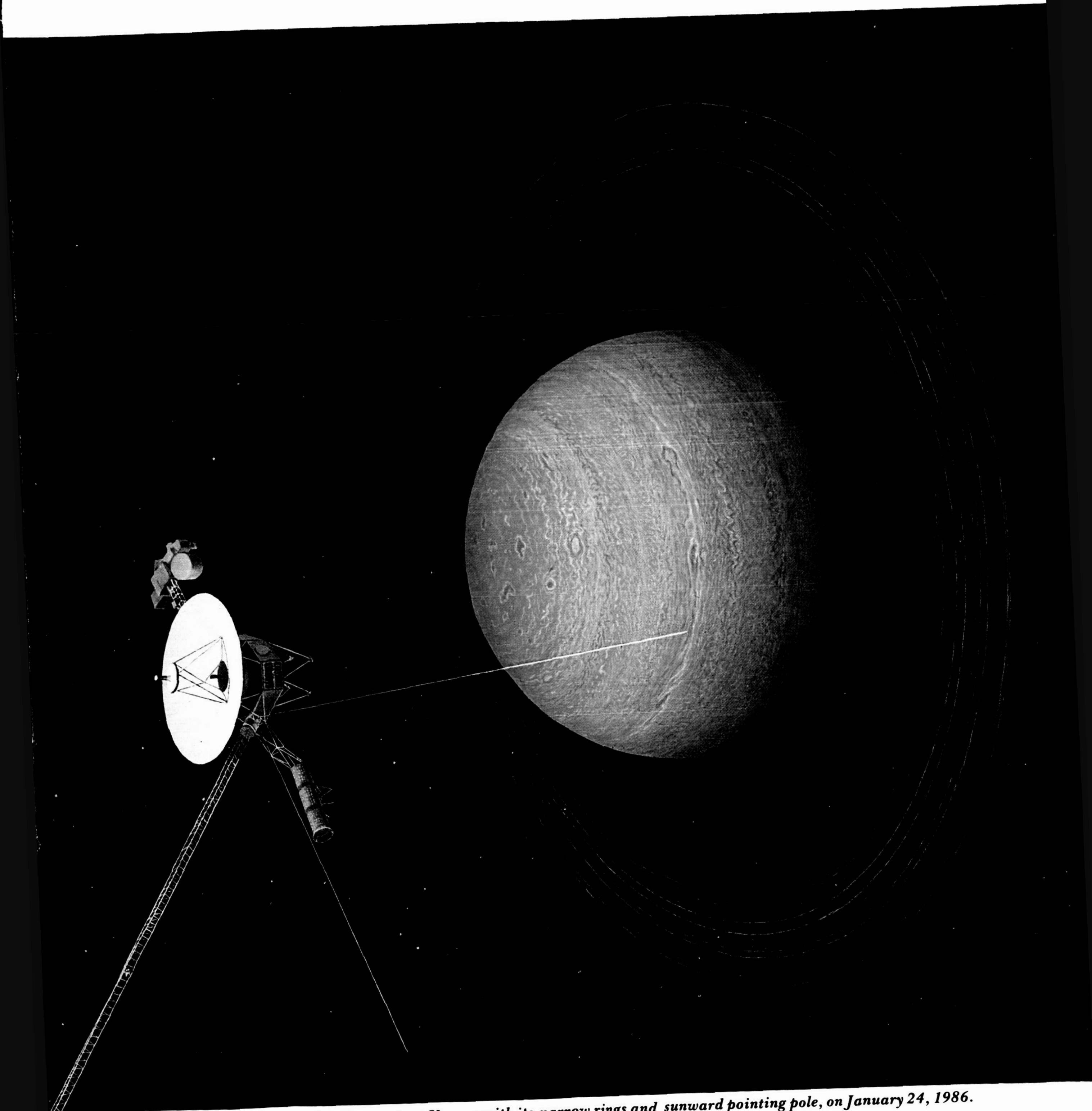
this stage we only know that Neptune and Pluto must come later because of the lack of suitable Jupiter swingby opportunities.

For these missions, the basic design for the probe follows that already developed for the *Galileo* project. The heat shield will require modifications in accord with the different entering velocities and atmospheric compositions, but several key changes in payload are also proposed (Figure 15).

The major changes from the *Galileo* payload in the case of the Titan probe would involve the substitution of a descent imager for the net flux radiometer and a gas chromatograph for the lightning detector and helium abundance determination. (The actual selection of instrumentation would, presumably, be accomplished through the customary process via an Announcement of Opportunity.) The descent imager would allow the acquisition of a least one image of Titan's surface, preferably with filters to obtain some spectral resolution. This instrument would also serve the same function as the present net flux radiometer, since it would carry upward-directed sensors as well. Since it serves this double purpose, the descent imager would be flown on other missions too, or the net flux radiometer could be substituted. The gas chromatograph would embody several new technical developments that allow this instrument to be smaller, lighter and more versatile than the *Pioneer Venus* model, while retaining a high sensitivity (10^{-9} for most gases). It will permit investigations of the organic molecules formed in Titan's atmosphere and provide supplementary data to those obtained by the neutral mass spectrometer on the identification and abundances of other constituents. Once again, this instrument could be flown to other

Figure 15: Recommended Instrumentation For Probe Missions Based On *Galileo* Probe Design

Instrument	Jupiter (Galileo)	Titan	Saturn	Uranus Neptune
Neutral Mass Spectrometer	X	X	X	X
Atmospheric Structure	X	X	X	X
Nephelometer	X	X	X	X
Net Reflectance Radiometer	X		X	X
Descent Imager		X		
Lightning Detector	X	—	X	X
Helium Abundance	X	—	X	X
Gas Chromatograph	—	X	X	X



Voyager 2 *will zoom past Uranus with its narrow rings and sunward pointing pole, on January 24, 1986.*

targets too, since it now appears that sufficient precision for the H/He determination can be obtained with a modern gas chromatograph.

For probe missions to Uranus and Neptune, the Working Group concluded that very high priority would be maintained even if the probe carrier spacecraft had no remote sensing instrumentation. Clearly preferable, however, are instrumented flyby spacecraft whose payload would include instrumentation selected from the following (radio science is assumed as included without added instrumentation):

LOW COST	Magnetometer Charged particle counters Dust particle impact detector
ADVANCED PAYLOAD	Radar (for Titan flyby) Far IR radiometer Imaging IR Spectrometer UV Spectrometer

This list of instruments, which is not intended to be exclusive, would also be suitable for the Saturn orbiter mission. The choice of bus payload would be determined by the availability of funds and the target planet. The inclusion of radar on a Titan probe mission was given very high priority, since it is our best hope for characterizing that satellite's surface. Even on a flyby mission about 20% of the satellite's surface could be "imaged." The far IR radiometer would allow measurements beyond the range covered by *Voyager's* IRIS (infrared interferometer spectrometer), thereby providing additional precision in the definition of the thermal spectra of these cold objects. This device would also probe the lower, convective regions of these planets' atmospheres as well as sensing the surface and lower atmosphere of Titan. The nature of the imaging device will depend on the specific mission and the results returned from Uranus and Neptune by *Voyager 2*. As another example, one might consider an imager for a Titan mission both for navigation and for a close pass of Iapetus. The infrared and ultraviolet spectrometers would again be designed to complement the instruments already flown by *Voyager*.

MISSION OPPORTUNITIES: Missions to Saturn and Titan can be launched regularly—every thirteen months. With the *Shuttle-Centaur*, direct trajectory missions are achievable for flyby/probe missions of Titan/Saturn (3-4 years) and also to Uranus (6-7 years). Direct orbiter missions to Saturn, using a newly developed, relatively light-weight spacecraft, would be possible with the aid of a Jupiter swingby (5-6 years). Also it is possible to send an orbiter/probe combination to Saturn using the *Shuttle-Centaur*. Specifically a *Galileo* orbiter/probe configuration could be launched to Saturn as early as 1987 on a ΔVEGA trajectory,* arriving at the planet in 1995. Such a mission would have almost total commonality with the *Galileo Jupiter* spacecraft and provides, potentially, an exceptional scientific return for the incremental cost.

Missions to Neptune and Pluto present more difficulty. Using the *Shuttle-Centaur*, a Jupiter gravity-assist is required to achieve reasonable trip times (less than 10 years).

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* A ΔVEGA trajectory is one in which a spacecraft is launched into a highly elliptical orbit around the Sun that brings it back around the Earth; the maneuver provides added velocity to the spacecraft (Δv), using Earth Gravity Assist (EGA).

Summary of Recommended Missions

TITAN PROBE/RADAR MAPPER
- First priority
- Launch 1992/Arrival 1995
- *Mariner Mark II* bus plus entry probe
- *Shuttle-Centaur* launch vehicle
- First *in situ* measurements
- First map of surface

SATURN PROBE
- *Mariner Mark II* plus entry probe
- *Shuttle-Centaur* launch vehicle
- Trip time less than four years
- First *in situ* measurements
- Comparison with Jupiter

SATURN ORBITER
- *Mariner Mark II*
- *Shuttle-Centaur* launch vehicle
- Trip time less than four years
- Extended measurements (two years) in Saturn system

URANUS PROBE
- *Mariner Mark II* bus plus entry probe
- *Shuttle-Centaur* launch vehicle
- Trip time less than 10 years
- First *in situ* measurements
- Comparison with Jupiter and Saturn

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SATURN ORBITER/TITAN PROBE
- Accomplishes two of highest priority missions
- Requires international cooperation
- Launch 1988 or 1989/Arrival 1996 or 1997
- *Galileo* orbiter plus entry probe
- *Shuttle-Centaur*
- ΔVEGA trajectory
- First *in situ* measurements on Titan
- Extended measurements (two years) in Saturn system
- First mapping of Titan surface

Inner Planets Missions

Venus Radar Mapper (VRM)

Science Rationale/Objectives

The next major step in exploration of the inner planets is the global reconnaissance of Venus' surface features to ascertain the geologic history and processes by which the surface has evolved, and to study the structure of the interior of Venus. Specific objectives are:

- Obtain a map of Venus for greater than 70% of the surface at resolution equivalent to optical imaging of one kilometer per line pair;
- Obtain radar altimetry data over as much of the planet as possible;
- Make gravity field measurements to augment those made by *Pioneer Venus Orbiter*.

Compelling Science Questions

1. What geological processes operate to form and modify the surface of Venus?
2. What is the age of the surface of Venus?
3. How old is the present atmosphere?
4. Did Venus have water and oceans?
5. Does Venus have plate tectonic activity?
6. What is the origin of the Venus highlands?
7. Why are topography and gravity positively correlated?
8. How does Venus rid itself of internal heat?
9. What can Venus tell us about Earth history?

Instruments and Expected Results

SYNTHETIC APERTURE RADAR: 1:5 million scale photomosaics of surface of Venus

RADAR ALTIMETER: 1:25 million scale topographic map at a spatial resolution of less than 50 km and a vertical range resolution of 100 m

RADIO (GRAVITY): 1:25 million scale gravity map of 76% of Venus at 700 km or better resolution and 2-3 milligals accuracy

Mission Scenario

A spacecraft will be launched in April, 1988, using a *Shuttle/Centaur G*. It will arrive at Venus in July, 1988 and be inserted into a near-polar, elliptical orbit 250 km by 10,300 km. Mapping will be executed for 42 minutes during that part of the orbit in which the spacecraft is closest to Venus. One hundred and ten minutes of the remainder of the orbit will be used for data playback from the on-board recorder. The primary mapping mission will end in April, 1989, after 243 days of mapping the entire surface.

Mars Geoscience Climatology Orbiter

Science Rationale/Objectives

The Earth, Venus and Mars form a related triad of inner solar system planets with atmospheres. Understanding their origin and the processes which define their evolutionary history represents an important goal. The study of Venus and Mars exploits the "natural experiments" they represent. The similarities and differences in the evolution of Venus and Mars illuminate, challenge, and improve our understanding of Earth. We may define the processes which have operated by observing their end products or, in the case of contemporary process, by observing them in action.

While our knowledge of Mars is extensive, it contains significant gaps. More importantly, there are a number of first order scientific questions that can be best addressed from an orbital platform. The *Mars Geoscience Climatology Orbiter* will provide new observations, not feasible from Earth or Earth-orbit, which extend and complement existing measurements and provide an improved basis for future intensive investigation. Specific objectives are:

- Determine the global elemental and mineralogical character of the surface;
- Determine the time and space distribution, abundance, sources, and sinks of volatile materials and dust over a seasonal cycle;
- Define globally the gravitational field and topography;
- Explore the structure and aspects of the circulation of the atmosphere;
- Establish the nature of the global magnetic field.

Compelling Science Questions

1. How does the elemental and mineralogical composition of the Martian surface relate to the surface type and relative age? How does surface composition relate to the planet's location in the solar system? What evidence does composition provide of internal energy sources and differentiation?
2. What is the distribution of condensed or trapped volatile material? What is the nature of the underlying residual south polar cap? Is there currently any net transport of water between hemispheres?
3. What are the mass distribution and figure of the planet? What are the structure, dynamics and strength of the interior and the thickness and strength of the crust? Does Mars possess an intrinsic magnetic field supported by a convecting core? What are the detailed topographic relationships along and across channels and between geologically distinct units?
4. How does the circulation of the atmosphere change with the seasons? What are the conditions which trigger and then suppress global dust storms? Do dust storms currently deposit material on the residual north polar cap?
5. What is the escape rate of atomic hydrogen and how does this rate vary? What is the interrelationship between atomic hydrogen, ozone, and water?

Instruments and Expected Results

GAMMA RAY SPECTROMETER: Elemental abundance—potassium, uranium, thorium, iron, titanium, silicon, oxygen, carbon, hydrogen

MAPPING VISUAL AND INFRARED SPECTROMETER: Mineralogy and condensates

INFRARED RADIOMETER: Profiles of temperature, water, and dust

RADAR ALTIMETER: Topography

RADIO SCIENCE: Gravitational field and refractory profiles

ULTRAVIOLET SPECTROMETER: Ozone profiles

ULTRAVIOLET PHOTOMETER: Atomic hydrogen column abundance

MAGNETOMETER: Intrinsic magnetic field

Mission Scenario

The mission could be launched in 1990 (with other opportunities in 1992, 1994, etc.) and after a one-year flight inserted into a polar orbit about Mars. Following a drift in this orbit to the desired sun angle, a small plane change (3 degrees) would be executed, producing a near circular (350 km altitude) sun synchronous mapping orbit from which observations would be made for a Mars year. The final orbit would be dictated by planetary protection requirements.

Venus Atmospheric Probe

Science Rationale/Objectives

The *Pioneer Venus* and *Venera* missions raised questions about the Venusian atmosphere that can only be answered by an atmospheric probe instrumented for *in situ* analysis. Verification of *Pioneer Venus* findings of large Ne and ^{36}Ar abundance and large Ar/Kr, Ar/Xe, and D/H ratios is needed. Precise values for $^{22}Ne/^{20}Ne$, $^{84}Kr/^{86}Kr$ and $^{132}Xe/^{129}Xe$ ratios are also required to place constraints on theories of origin of planetary atmospheres. Oxidation state of the lower atmosphere, H_2 and water abundances and density profiles for sulfur compounds H_2S, COS, sulfur dioxide have also been identified as major questions for resolution as a result of *Pioneer Venus* and *Venera* measurements.

To determine the composition of the atmosphere of Venus and, in particular, to measure with precision the abundance of the noble gases—helium through xenon.

Compelling Science Questions

1. How did the atmosphere originate and evolve to its present state?
2. Did Venus once have oceans?
3. What is the composition of the haze layer high in the atmosphere?
4. Why is the high atmosphere so cold at night?
5. How does heat circulate in the lower atmosphere?
6. What is the sulfur cycle in the lower atmosphere?

Instruments and Expected Results

Baseline:

NEUTRAL MASS SPECTROMETER: Chemical composition and physical state of the atmosphere as a function of altitude; isotopic ratios

GAS CHROMATOGRAPH: Atmospheric profiles of trace constituents including the noble gases (neon, argon, krypton), sulfur compounds (hydrogen sulfide, carbonyl sulfide, sulfur dioxide), and water

PRESSURE, TEMPERATURE, AND ACCELERATION SENSORS: Mean molecular mass of the atmosphere; upper atmospheric pressure, temperature, and density profiles; horizontal wind velocity, wind shear, vertical flow, and atmospheric turbulence

Possible enhancements:

DIFFERENTIAL THERMAL ANALYZER: Composition of aerosols

X-RAY FLUORESCENCE: Composition of particles (dust) within aerosols

VISUAL SPECTROPHOTOMETER: Water abundance

DESCENT IMAGER: Characterization of surface morphology before impact

CLOUD PARTICLE COUNTER: Number density and size distribution of cloud particles

Mission Scenario

The baseline mission includes a *Pioneer Venus*-like probe and probe bus which can be launched to Venus during any launch opportunity (every 19 months) by the *STS/PAM-A*. The probe would be targeted for a daylight entry and would transmit data directly to Earth. Minor changes would allow expansion of the target area. Alternatively it would be possible to insert a Venus atmospheric probe during the Venus swing-by phase of a Mercury flyby mission.

Mars Aeronomy Orbiter

Science Rationale/Objectives

As part of the effort to understand and compare the inner planets, it is necessary to extend knowledge of the Martian upper atmosphere and ionosphere. Specific objectives are:

- Determine the diurnal and seasonal variation of the upper atmosphere and ionosphere;
- Determine the solar wind interaction with the planetary atmosphere;
- Verify whether Mars possesses an intrinsic magnetic field;
- Measure the present thermal and nonthermal escape rates of atmospheric constituents (hydrogen, oxygen, nitrogen) and determine what these escape rates imply for the history and evolution of the Martian atmosphere.

Compelling Science Questions

1. Does Mars possess an intrinsic magnetic field?
2. What are the diurnal and seasonal variations of the upper atmosphere and ionosphere and how do they compare to Earth and Venus?
3. What are the characteristics of the solar wind interaction with Mars and how do they vary during a Martian year?
4. What are the escape rates of important gases such as hydrogen, oxygen, and nitrogen, and what do they imply concerning the history of Mars' atmosphere?

Instruments and Expected Results

NEUTRAL MASS SPECTROMETER: Densities, scale heights, winds and temperatures of neutral species

THERMAL ION MASS SPECTROMETER: Spatial and temporal variations in composition of the ions in the atmosphere

ELECTRON TEMPERATURE PROBE: Thermal structure of the electron gas in the ionosphere

RETARDING POTENTIAL ANALYZER/DRIFTMETER: Investigate the thermal structure and drift velocities of ions and electrons and suprathermal electrons up to 70 electron volts

MAGNETOMETER: Characterization of the magnetic field and the interaction between solar wind and the ionosphere

SOLAR WIND PLASMA ANALYZER: Measurement of the interaction between the solar wind and the ionosphere; spectra of suprathermal electrons above 50 electron volts

ELECTRIC FIELD DETECTOR: Determination of the manner in which the solar wind deposits energy into the upper atmosphere through wave particle interaction

FABRY PEROT INTERFEROMETER: Dynamics of the upper atmosphere from velocities and temperature structure of key atmospheric species

ULTRAVIOLET SPECTROMETER: Hydrogen distribution, airglow intensities, and other structure of the upper atmosphere

Mission Scenario

The mission could be launched in July 1988 and every two years thereafter, into a high elliptical (3 Mars radii by 150 km) orbit with 77.5° inclination. During one Mars year, the orbit will provide periapsis sampling at all latitudes and local times. A mission lifetime of at least one Martian year is necessary to provide a complete seasonal survey.

Mars Network Mission

Science Rationale/Objectives

The general objective is to establish a global network of seismic stations, meteorological stations, and geochemical and geophysical observation sites that operate on Mars for a long period of time. This objective can be accomplished by the emplacement of penetrators, which are missile-like projectiles that impact the surface at high velocity and become buried, leaving a small afterbody at the surface that transmits data. The penetrator and afterbody contain a wide variety of instruments, but their unique advantage is in emplacement into the ground and in providing a network that can operate for an extended period. A very large network is required to obtain a general circulation model, but the other objectives can be addressed in part by a minimum of 3-6 stations. Specific objectives are:

- Determine the chemical composition of Martian near-surface material;
- Determine the internal structure and seismicity of Mars;
- Determine the general circulation of the Martian atmosphere;
- Characterize the local atmospheric conditions in different Martian areas.

Compelling Science Questions

1. What is the chemical composition of the crust of Mars?
2. What is the structure of Mars' interior?
3. What is the nature of Mars' seismicity?
4. How does the atmosphere circulate at present and how has the Martian climate evolved?

Instruments and Expected Results

GAMMA-RAY SPECTROMETER: Analysis of naturally occurring radioactive elements (potassium, lanthanum, lutetium, thorium, uranium) and of elements activated by cosmic rays (iron, magnesium, titanium, oxygen, silicon, etc.)

PULSED NEUTRON SPECTROMETER: Elemental analysis of major rock-forming elements, plus carbon, oxygen, and hydrogen up to about 1 m from the penetrator

SEISMOMETER: Seismicity, thickness of regolith, possibly structure of Martian interior

PRESSURE AND TEMPERATURE SENSORS ON THE AFT BODY: Local weather patterns

Mission Scenario

The penetrators would be released on approach, one-by-one, and directed toward the appropriate target. Entering behind a deployable heatshield and falling on a parachute, each probe would bury itself in the Martian surface, leaving some instrumentation and an antenna at the surface. Communications to Earth would be via an orbiting spacecraft which would interrogate each probe at least once per day. RTG and battery power would provide for prolonged surface operations designed to allow seismic and meteorological data to be gathered over an extended period.

Mars Surface Probes

Science Rationale/Objectives

The bulk chemical composition, including key trace elements, is a fundamental property of a planet and it has immense cosmochemical significance. Its measurement was one key reason for the high priority that was assigned to a Mars sample return by COMPLEX. New analytical tools and a well-studied cosmochemical model make this measurement accessible to a low cost dedicated mission. Specific objectives are:

- Perform elemental analysis, including trace elements and light elements, of volcanic rock;
- Perform chemical analysis of ice cap material and permafrost;
- Perform measurements of Martian seismicity;
- Characterize local weather conditions in different Martian areas.

Compelling Science Questions

1. What is the bulk chemical composition?
2. What is the nature of Mars' seismicity?

Instruments and Expected Results

GAMMA-RAY SPECTROMETER, PULSED NEUTRON SPECTROMETER: Analysis of naturally occurring radioactive elements (potassium, lanthanum, *lutetium*, *thorium*, uranium) and of elements activated by cosmic rays (iron, magnesium, titanium, oxygen, silicon, etc.) Elemental analysis of major rock-forming elements, plus carbon, oxygen, and hydrogen up to about 1 m from the penetrator

SEISMOMETER: Seismicity, thickness of regolith, possibly structure of Martian interior

PRESSURE, TEMPERATURE SENSORS ON THE AFT BODY: Local weather patterns

Mission Scenario

The penetrators can be released upon approach from a simple carrier and targeted for volcanic areas or ice caps identified on existing images. Location could be determined from tracking, nested entry images, or after-body imaging. The pulsed neutron spectrometer requires only a short period of detector cooling and data transmission. Data would be transmitted either to an existing orbiter, or to the carrier in a highly elliptical orbit. Such a simple penetrator mission would be an excellent precursor for an eventual network of more complex, instrumented penetrators.

Lunar Geoscience Orbiter

Science Rationale/Objectives

- Measurement of elemental and mineralogical surface composition;
- Assessment of global resources, including a search for frozen volatiles at poles;
- Measurement of global figure and surface topography;
- Measurement of global gravity field.

Compelling Science Questions

1. What is the compositional heterogeneity of the Moon and what was the time sequence of lunar differentiation? How does this constrain theories of lunar origin and thermal history?
2. How do the detailed surface elemental and mineralogical phase composition vary globally?
3. What is the detailed lunar gravitational field? How does it correlate with surface composition?
4. How do surface composition and gravity variations relate to magnetic variations?
5. What is the origin of localized magnetization in the lunar surface? Are these magnetic anomalies old or young? Did they result from the transient effects of impacts or are they evidence of former existence of a global magnetic field?
6. What is the internal density distribution of the Moon?
7. What is the nature and time distribution of explosive volcanism on the Moon?
8. Are there volatile materials such as water ice trapped in the polar regions of the Moon?

Instruments and Expected Results

MAPPING SPECTROMETER: Surface mineral composition - feldspars, pyroxenes, olivines and condensed volatiles

GAMMA-RAY SPECTROMETER: Answer the question of cold-trapped volatiles in the polar regions;
Surface elemental composition - silicon, aluminum, magnesium, iron, titanium, calcium, sodium, uranium, thorium, potassium;
Global resource survey

RADAR ALTIMETER: Global figure and surface topography

RADIO TRACKING: Near side gravity field and large-scale gravity anomalies

Possible Enhancement:

MAGNETOMETER AND ELECTRON REFLECTOMETER: Local magnetic fields and surface anomalies

IMAGING: Understand geologic processes and lunar history

Mission Scenario

Launch at almost any time and insert into an initial elliptical orbit with low periapsis (less than 30 km) on anti-sunward side for Gamma-Ray Spectrometer calibration and magnetic measurements followed by a one-year observation period at a 50-100 km circular polar orbit.

Nearly identical instruments could be used to study a near-Earth asteroid and it may be cost effective to send an *LGO* spacecraft to a near-Earth asteroid after completion of the lunar study.

Comet Rendezvous

Science Rationale/Objectives

Comets are considered the most primitive bodies in the solar system; this mission will provide a detailed study of one of these bodies. Specific objectives are:

- Study the cometary nucleus through a complete perihelion passage, characterizing changes in the nucleus, coma, and tail as a function of time and orbital position;
- Determine the chemical/isotopic composition of volatile/non-volatile fractions of the nucleus and coma;
- Describe the size, shape, mass, rotation period/pole orientation of the cometary nucleus, mapping its surface geomorphology, albedo, thermal properties, etc.;
- Characterize the hydrodynamics of gas and dust outflow;
- Determine the chemical kinetics of parent and daughter molecules in the coma;
- Characterize solar wind interaction with the coma.

These studies will provide complementary data to the data provided by the 1986 Halley flyby missions which will provide a preliminary view of an active short-period comet.

(Options: One or more asteroid Flybys prior to Rendezvous; dual atomized mission with sample return launched in 1994)

Compelling Science Questions

1. What does a comet nucleus look like? Is it a dirty snowball? What is its size, shape, and surface morphology? Is it cratered? Does it have a crust of debris? Does material boil off from all parts of the comet or only in discrete jets?
2. How continuous or how sporadic is the emission of gas and dust?
3. What atmospheric and surface changes occur as the comet approaches and then moves away from the Sun?
4. What is a comet made of? What are the abundances of the various elements in the nucleus? What minerals and ices lie on the comet's surface? What volatile molecules escape from the comet?
5. What are the physical structure and chemical composition of cometary dust grains? Are they all similar or are there many different types? How abundant are dust particles of various sizes?
6. What are the mass and bulk density of the comet nucleus?
7. What is the generic relation of comets to interstellar dust grains, to meteorites, to asteroids, and to the planets? Are comets pristine samples of the solar nebula or have they undergone some type of processing? Could comets have been the building blocks of the outer planets? Is it likely that comets contributed substantial amounts of material to the atmospheres of the terrestrial planets?
8. What is the nature of the solar wind interaction with the cometary coma?

Instruments and Expected Results

IMAGING: Detailed characterization of time variable morphology of nucleus, coma and tail

X-RAY AND GAMMA-RAY SPECTROMETERS: Elemental composition of nucleus

NEUTRAL AND ION MASS SPECTROMETERS: Elemental, molecular and ion composition and density of coma as function of time and position in the coma

DUST COLLECTOR AND ANALYZER: Elemental composition and physical characteristics of dust

DUST COUNTER: Dust size distribution and rate of dust loss from the nucleus as functions of time

IR REFLECTANCE SPECTRAL MAPPER: Mineral phase and composition of the nucleus and composition of the coma as a function of time

MAGNETOMETER AND PLASMA WAVE: Intrinsic magnetic field and nature of interaction of solar wind with cometary coma

Mission Scenario

Following launch on the *Shuttle-Centaur* the comet rendezvous spacecraft cruises for about 5 years towards its destination; propulsive maneuvers match the trajectory of spacecraft and comet several months before perihelion passage of the comet. Thereafter only small propulsive maneuvers are required to maintain station keeping and examine the comet from any desired distance and direction. Remote sensing measurements begin immediately and as the comet approaches the sun the *in situ* instrumentation measures the increasingly active expulsion of dust and gases. If necessary the spacecraft backs off to a safe distance, resuming a close rendezvous after the activity subsides. Spacecraft is then inserted into a close (several to 10 km) circular polar mapping orbit. The end of mission occurs about six months after the initial rendezvous.

Comet Atomized Sample Return

Science Rationale/Objectives

Comets are the most primitive bodies in the solar system and are the best source of obtainable samples of the original material from which it was formed. Comets may provide a cosmochemical record of conditions in the interstellar medium and the primordial solar nebula. Scientific objectives are:

- Obtain samples of the volatile and non-volatile constituents of the coma during a fast fly-through and return them to Earth for analysis;
- Determine the densities of coma materials along the flight path.

Compelling Science Questions

1. What are the elemental and isotopic compositions of individual comet dust grains?
2. What minerals are comet grains made of?
3. How do comet dust grains compare to chondrites or other classes of meteorites?
4. What are the isotopic ages of large dust grains?

Instruments and Expected Results

Baseline:

SAMPLE COLLECTION MODULE: Collection of hundreds of individual dust and gas samples, recondensed from plasma

DUST COUNTER: Dust density along flight path

IMAGING:* Size, shape and rotational properties of nucleus; Location of active sites on nucleus

NEUTRAL MASS SPECTROMETER: Density and composition of gas along flight path

Possible Enhancement:

ION MASS SPECTROMETERS: Ion composition and density of coma

IR REFLECTANCE SPECTRAL MAPPER: Phase composition of the nuclear surface and composition of the coma as a function of time

* Not mandatory for terminal navigation if mission is carried out in conjunction with rendezvous mission.

Mission Scenario

The spacecraft, launched on *Shuttle-IUS*, travels on a ballistic trajectory that reaches the comet after typically two years. Remote sensing instrumentation, if carried, is turned on about 60 days before encounter, which is very close to perihelion. Imaging data are used for terminal navigation unless rendezvous spacecraft is already on station, providing an accurate determination of comet location. Flythrough of the cometary coma takes place at 10-15 km/sec and lasts only minutes, but allows for collection of atomized dust grains and gases. After the encounter the dust collector panels are stored in an on-board capsule. A relatively small propulsive maneuver places the spacecraft on an impact trajectory with the Earth. The sample capsule enters the atmosphere directly and parachutes to the surface for recovery.

Mainbelt Asteroid Multiple Orbiter/Flyby

Science Rationale/Objectives

Asteroids have remained relatively unchanged since their formation early in the evolution of the solar system; this mission will provide a detailed study of several asteroids. Specific objectives are:

- Characterize asteroids of various types, including determinations of size, shape, rotation, albedo, mass, density, surface morphology, surface composition, magnetic field and solar wind interaction;
- Provide a more detailed study of one or two selected Mainbelt asteroids, emphasizing elemental and mineralogical composition and detailed morphology.

Compelling Science Questions

1. What do asteroids look like? What are their sizes, shapes, and surface morphologies? How fast do they rotate and in what direction?
2. What are asteroids made of? What are their masses and bulk densities? What are their chemical compositions? What minerals are present on their surfaces?
3. Are asteroids magnetized? If so, which ones, how strongly, and how uniformly?
4. What geological processes have occured?
5. Are some asteroids the broken remains of larger bodies? Do asteroids have regoliths?
6. What are the similarities and differences among the various types of asteroids? What are the probable causes of the differences?

Instruments and Expected Results

IMAGING: Size, shape, rotation, surface morphology

X-RAY AND GAMMA-RAY SPECTROMETERS: Elemental composition (rendezvous)

IR REFLECTANCE SPECTRAL MAPPER: Mineralogical composition

MAGNETOMETER: Intrinsic magnetic field, nature of solar wind interaction

Mission Scenario

For opportunities identified to date the spacecraft is launched on the *Shuttle-Centaur* and reaches its first target after a flight time of about four years during which one or more gravity assists are provided by Mars or Jupiter. After a propulsive maneuver the spacecraft matches orbit with its target (which if large enough will lead to an orbital capture by the asteroid). Observations are made over a several week period after which the spacecraft is placed on a new trajectory taking it past several representative asteroids (about 50 km diameter) on its way to a possible second rendezvous with another body. During the flybys remote sensing observations are made and the spacecraft trajectory is tracked to provide a determination of the mass of each object. At the second principal target the spacecraft matches orbits and remains with this body until the end of its mission several months later. Total mission life from launch is about six years.

Earth-Approaching Asteroid Rendezvous

Science Rationale/Objectives

Unlike Mainbelt asteroids which generally remain near their positions of origin, Earth-approaching asteroids are in unstable orbits. Some may be fragments of disrupted Mainbelt asteroids, while others are probably dead comet nuclei. They are almost certainly related to some meteorites and may eventually be a valuable source of materials for use in space. The specific objectives:

- Determine the size, shape, rotation, mass and density of the body;
- Determine the albedo, surface morphology, and surface composition;
- Measure the magnetic field and solar wind interaction.

Compelling Science Questions

1. What is the composition of the body and how does it relate to meteorite specimens?
2. What geologic processes have occurred on the body?
3. Is the asteroid a dead comet nucleus or a piece of a larger, broken asteroid? What is its origin?
4. What are the similarities and differences among the various types of asteroids?

Instruments and Expected Results

IMAGING: Size, shape, rotation, surface morphology

X-RAY AND GAMMA-RAY SPECTROMETERS: Elemental composition (rendezvous)

IR REFLECTANCE SPECTRAL MAPPER: Mineralogical composition

MAGNETOMETER: Intrinsic magnetic field, nature of solar wind interaction

Mission Scenario

The spacecraft is launched on a *Shuttle-IUS* or *Shuttle-IUS-Star 48*. About five opportunities for launch are available in any year. Flight time to reach the object is 1-2 years. After a propulsive maneuver to match orbits, the spacecraft remains with the target asteroid for several months during which time a detailed characterization of the asteroid is made from all angles.

Titan Flyby/Probe

Science Rationale/Objectives

The atmosphere of Titan is uniquely interesting from the standpoint of organic chemical evolution. The organic chemistry now taking place on Titan provides the only planetary-scale laboratory for studies of processes that may have been important in the pre-life terrestrial atmosphere. Specific objectives are:

- Determine the structure and chemical composition of the atmosphere;
- Determine the exchange and deposition of energy within the atmosphere;
- Characterize, at least locally, the surface morphology of Titan.

Compelling Science Questions

1. How did Titan develop its present atmosphere?
2. What gases and aerosols are present at different heights in Titan's atmosphere?
3. What chemical processes are occurring in Titan's atmosphere? What organic molecules are present and what might they tell us about the origin of life on Earth?
4. What is the temperature profile of Titan's atmosphere, and what governs it?
5. What are the nature and structure of clouds in Titan's atmosphere?
6. What is the energy source for the ultraviolet dayglow?
7. What is the chemical composition of Titan's orange haze?
8. How much sunlight reaches Titan's surface and what is its extinction profile in the atmosphere?
9. What does the surface of Titan look like? Are there lakes or oceans of methane? What are the major geological features of any land or ice masses? How much organic matter has accumulated and in what form?
10. What was the condition of the protoplanetary solar nebula in the area of Titan?

Instruments and Expected Results

Pre-entry Science:

ION MASS SPECTROMETER: Composition of the ionosphere

NEUTRAL MASS ISOTOPIC SPECTROMETER: Number density identification, and ratios of neutral upper atmosphere constituents

RETARDING POTENTIAL ANALYZER: Thermal plasma properties and structure of the upper atmosphere

ELECTRON TEMPERATURE PROBE: Electron temperatures and electron and ion densities

Descent Module:

NEUTRAL MASS SPECTROMETER: Number density, vertical profile, identification, and isotopic ratios of atmosphere constituents

PRESSURE, TEMPERATURE, AND ACCELERATION SENSORS: Mean molecular mass of the atmosphere; upper atmospheric density profile and lower atmosphere pressure, temperature and density profiles; horizontal wind velocity, wind sheer, vertical flow, and atmospheric turbulence.

NEPHELOMETER: Physical structure and location of cloud layers

GAS CHROMATOGRAPH: Profiles of trace constitutents including the noble gases (neon, argon, krypton), organics (hydrogen cyanide, propane, acetylene, etc.) and carbon monoxide

DESCENT IMAGER/RADIOMETER: Vertical distribution of atmospheric constitutents such as methane and ammonia and aerosols by measuring relative light levels at near-infrared and visible wavelengths. Images prior to impact will provide a closeup look at the surface and topography

Flyby Science:

RADAR: Surface topography

RADIO SCIENCE: Temperature and pressure profiles in planetary atmospheres from radio occultations

MAGNETOMETER AND CHARGED PARTICLE DETECTOR: Electrical and magnetic field characteristics and charged particle fluxes of (possible) magnetosphere

DUST PARTICLE DETECTOR: Determination of particle distribution

Mission Scenario

The mission involves a *Galileo*-like probe, either carried to Titan on-board a flyby carrier spacecraft or a Saturn Orbiter. Launches to Titan can be accomplished every 13 months and a trip time of about 3.5 years is required for a *Probe/Flyby* mission or about 6.5 years for a *Probe/Orbiter* mission with the *Centaur F/STAR 48* upper stage combination. As the carrier approaches Saturn, the Probe is deployed into the Titan atmosphere. Probe release from carrier spacecraft would occur at T-20 days (T is the time of closest approach to Titan) with probe atmospheric entry at T-2 hours. Probe descent time would last approximately one hour to T-1 hr. Potential radar and IR mapping from the carrier spacecraft would last from T-1 hr to T+1 hr. Possible Saturn system exploration would extend from T-30 days to T+30 days. A much more extended study (about 2 years) of the Saturn system would be possible with an orbiter.

Outer Planets Flyby/Probes (Saturn, Uranus, Neptune)

Science Rationale/Objectives

Unlike the terrestrial planets, the giant outer planets offer us an opportunity to address the key questions about their internal structures and bulk compositions through detailed studies of compositions of their atmospheres. *In situ* measurements of isotopic and molecular compositions in the outer planet atmospheres will also provide diagnostic information on the protoplanetary condition and radial properties in that region of the Solar nebula. In addition, regions of the atmospheres of the Outer Planets possess cloud aerosol layers of an interesting chemical nature; and the transport of energy within the atmosphere is important to an overall understanding of the internal structure and the evolution of the planet. The specific objectives are:

- Determine the chemical composition and physical condition in the Outer Planets' atmospheres;
- Compare Jupiter, Saturn, Uranus, and Neptune.

Compelling Science Questions

1. What is the reason for the significant variation of the chemical and thermal properties of Jupiter and Saturn as a pair and Uranus and Neptune as a pair? Why are Uranus and Neptune so different from each other?
2. What are the abundances of helium, hydrogen, trace constituents? What are the isotopic ratios of the major elements?
3. What is the vertical structure of the atmospheres?
4. What is the structure and composition of cloud and aerosol layers?
5. What is the transport and deposition of energy in the atmosphere?
6. Is there electrical activity in the atmospheres?
7. What are the relative isotopic abundances in the atmosphere?
8. What was the condition of the protoplanetary nebula in these areas of the solar system?
9. How did the planet evolve?
10. What is the nature of the satellites, rings, magnetic fields, and atmospheric dynamics?

Instruments and Expected Results

Baseline:

NEUTRAL MASS SPECTROMETER: Number density, vertical profile, identification, and isotopic ratios of atmospheric constituents

PRESSURE, TEMPERATURE, AND ACCELERATION SENSORS: Mean molecular mass of the atmosphere; upper atmospheric density profile and lower atmosphere pressure, temperature and density profiles; horizontal wind velocity, wind shear, vertical flow, and atmospheric turbulence.

NEPHELOMETER: Physical structure and location of cloud layers

HELIUM ABUNDANCE DETECTOR: Accurate hydrogen/helium abundance ratio in the atmosphere

LIGHTNING AND RADIATION DETECTOR: Verification of the presence of lightning; scale size of cloud turbulence

NET FLUX RADIOMETER: Location of cloud layer; variation in the mixing ratios of atmospheric constituents, energy transport and deposition in the atmosphere

Possible Enhancements:

GAS CHROMATOGRAPH (substitution for helium abundance detector and lightning radiation detector): Profiles of trace constituents including noble gases (neon, argon, krypton), organic and inorganic molecules, sulfur compounds and water

Flyby Science:

RADIO SCIENCE: Temperature and pressure profiles in planetary atmospheres from radio occultations

MAGNETOMETER AND CHARGED PARTICLE DETECTOR: Electrical and magnetic field characteristics and charged particle fluxes of (possible) magnetosphere

DUST PARTICLE DETECTOR: Determination of particle distribution

Mission Scenario

The baseline mission includes a *Galileo*-like probe and Probe Carrier spacecraft. Launches to the outer planets require a *Centaur F/STAR 48* upper stage combination and can be launched approximately every 13 months. Missions to Saturn require approximately 3.5 years. Mission to the far Outer Planets can be accomplished in about 5.5 years to Uranus and 9.5 years to Neptune if a very light carrier like the *Pioneer 10/11* spacecraft is used.

Saturn Orbiter

Science Rationale/Objectives

The *Saturn Orbiter* will provide an understanding of the behavior of this complex assembly of satellites, field phenomena, rings, and giant planet not possible without investigation over an extended period of time. Orbit changes over the duration of the mission are possible with Titan encounters which will allow detailed mapping and exploration of Titan, an aerosol shrouded body thought to be similar in some ways to our pre-biotic Earth. Specific objectives are:

- Determine the three dimensional structure and dynamical behavior of the rings;
- Determine the composition of satellite surfaces (minerals and ices) and geological history of each object:
- Determine the nature and origin of the dark material on Iapetus' leading hemisphere;
- Measure the three dimensional structure and dynamical behavior of the magnetosphere;
- Study the dynamical behavior of Saturn's atmosphere at cloud level;
- Study the time variability of Titan's clouds/hazes;
- Characterize Titan's surface on a regional scale.

Compelling Science Questions

1. What is the three-dimensional fine structure of Saturn's rings?
2. What causes the transient spokes in the rings?
3. What are the size distribution, chemical composition, and physical state of the ring particles?
4. What does the surface of Titan look like? Are there lakes or oceans of methane? What are the major geological features of any land or ice masses?
5. What are the Saturn satellites made out of? What minerals and ices are present on their surfaces?
6. What is the composition of Saturn's atmosphere? How does it circulate and change with time? What is the radiative energy balance within the atmosphere?
7. What is the three-dimensional structure of Saturn's magnetosphere? What are the sources, circulation patterns, and sinks of its mass and energy?
8. How do the properties of the magnetosphere vary in response to changes in the solar wind?
9. What is the interaction of magnetospheric fields and particles with ring particles and with Saturn's satellites?

Instruments and Expected Results

IMAGING: Ring characteristics, satellite surface morphology; Saturn and Titan atmospheric dynamics

IR RADIOMETER: Thermal emission as a function of depth in Saturn's atmosphere; Satellite surface thermal characteristics

UV RADIOMETER: Saturnian atmospheric airglow, ring structure to 20 m resolution via stellar occultations

RADAR: Gross morphology, including liquid/solid phase of Titan's surface

MAGNETOMETER, CHARGED PARTICLE DETECTOR AND PLASMA WAVE ANALYSER: Electrical and magnetic field characteristics and charged particle fluxes of magnetosphere

DUST PARTICLE DETECTOR: Determination of particle distribution outside region of rings

RADIO SCIENCE: Temperature, pressure profiles in Saturn and Titan atmospheres; particle size distribution in rings

Mission Scenario

The spacecraft would be launched using the *Shuttle Centaur* and would reach its destination after a flight of about 3½ years. Launch opportunities occur in almost every year (on 13 month centers). The spacecraft would be propulsively decelerated at Saturn, also taking advantage of Titan's gravity field. Many close flybys of the many Saturnian moons would be achieved during an orbital phase lasting about two years. Ring measurements would be acquired from the complete range of observational phase angles, including numerous stellar and radio occultations. *In situ* measurements of the Saturnian magnetosphere would be made for a large range of geometries with respect to the incident solar wind. Imaging of the Saturnian clouds would take place on each orbit from high altitude while IR sounding of the atmosphere would be achieved from near periapsis.

APPENDIX II U.S. Lunar and Planetary Missions Through 1982

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
Mariner II	Aug. 27, 1962	Venus	Planetary exploration: first successful interplanetary probe. Found no magnetic field; high surface temperatures of approximately 800°F. Passed Venus Dec. 14, 1962 at 21,600 miles, 109 days after launch.
Ranger VII	July 28, 1964	Moon	Lunar exploration (photography): Camera system yielded 4,300 high resolution TV pictures with about 2,000 times better definition than present Earth-based photography; objects less than three feet in diameter discernible. Impact occured July 31, 1964, 68 hours, 36 minutes after launch in Sea of Clouds region, 8-10 miles from aim point.
Mariner IV	Nov. 28, 1964	Mars	Planetary and interplanetary exploration: Encounter occurred July 14, 1965 with closest approach 6,100 miles. Twenty-two pictures taken.
Ranger VIII	Feb. 17, 1965	Moon	Lunar photography: 7,100 pictures obtained; impact occurred Feb. 20, 1965, about 15 miles from target in Sea of Tranquility. Total flight time to impact: 64 hours, 53 minutes.
Ranger IX	Mar. 21, 1965	Moon	Lunar photography: 5,800 pictures obtained; impact less than three miles from target in eastern floor of crater Alphonsus. Pictures converted for "live" viewing on commercial TV. Final mission of *Ranger* series. Total flight time to impact on Mar. 24, 1965, 64 hours, 31 minutes.
Surveyor I	May 30, 1966	Moon	Lunar exploration: Achieved soft lunar landing on first engineering test flight (with closed loop guidance) at 02:17 EDT June 2, 1966, at 2.41°S, 43.43°W (Ocean of Storms). Data obtained on morphology and lunar origin; bearing strength of *Surveyor I* site and footpad scale about three psi; surface material found to be small, cohesive particles with rocks up to three feet in size; no loose dust. 10,300 pictures taken during first lunar day; 900 during second, last contact Jan. 7, 1967.
Lunar Orbiter I	Aug. 10, 1966	Moon	Lunar photography: Total of 207 frames of medium and high resolution pictures taken; 38 from initial orbit, 169 from low orbit. Areas covered: nine primary and seven potential *Apollo* landing sites (including *Surveyor I* site), 11 backside and two Earth-Moon pictures. Medium resolution pictures good, high resolution smeared. Readout completed Sept. 13, 1966; intentionally impacted Oct. 29, 1966 to avoid interference with second mission.
Lunar Orbiter II	Nov. 6, 1966	Moon	Lunar photography: Spacecraft completed taking 211 frames of 422 medium and high resolution pictures on Nov. 26, 1966. Spacecraft responded to over 2,870 commands and performed over 280 maneuvers. Readout completed Dec. 6, 1966. Impacted Oct. 11, 1967.
Lunar Orbiter III	Feb. 5, 1967	Moon	Lunar photography: 422 medium and high resolution pictures taken. Readout completed for six primary sites, parts of six other sites. Partial readout returned on 31 secondary sites. Impacted Oct. 9, 1967.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
Surveyor III	April 17, 1967	Moon	Lunar exploration: Achieved soft landing on April 20, 1967. Closed loop radar failed during landing and spacecraft landed three times on inertial guidance before its verniers cut off. Surface sampler experiment discovered pebbles at six inches depth and 10 psi bearing strength. The spacecraft returned 6,300 pictures. Site: Oceanus Procellarum, 3.33°S, 23.17°W.
Lunar Orbiter IV	May 4, 1967	Moon	Lunar photography: First photos returned May 11, 1967. Problems developed with camera thermal door. Readout completed May 27, 1967. High resolution photos lunar taken of over 99% of frontside. Impacted Down Oct. 6, 1967.
Mariner V	June 14, 1967	Venus	Planetary exploration: All science and engineering subsystems nomal through encounter with Venus; data indicates Venus has a Moon-like effect on solar plasma and strong H_2 corona comparable to Earth's, 72% to 87% CO_2 atmosphere with balance probably nitrogen, O_2. Closest approach. 3,900 km on Oct. 19, 1967.
Lunar Orbiter V	Aug. 1, 1967	Moon	Lunar photography: Last launch in the series of missions to of perform mapping of entire lunar surface. Provided detailed coverage of 36 scientific sites; five *Apollo* sites; completed high altitude far side coverage; a full view of Earth in near full phase. One hundred percent readout accomplished of all 212 frames taken; provided near-lunar micrometeoroid and radiation data. Impacted Jan. 31, 1968.
Surveyor V	Sept. 8, 1967	Moon	Lunar exploration: First alpha scatter data; indicated basaltic character of area sampled in Mare Tranquillitatus, 23.19° E and 1.52°N. Achieved 83 hours alpha scatter data and 18,006 photos in first lunar day. Survived first lunar night but, as expected, subsequent data obtained of lower quality.
Surveyor VI	Nov. 7, 1967	Moon	Lunar Exploration: Sinus Medii, 0°25'N, 1°3'W Nov. 10, 1967. 30,100 TV pictures, 27 hours surface alpha scatter analytical time obtained. First liftoff from lunar surface: moved 10 feet to a new location. Sixth in a series of seven *Surveyor* flights intended to perfect the technology of soft landing on the moon and provide basic scientific and engineering data in support of *Apollo*.
Surveyor VII	Jan. 7, 1968	Moon	Lunar exploration: Last *Surveyor;* emphasized scientific objectives, landed on Tycho ejecta blanket, 40.89°S, 11.44°W Jan. 10, 1968; first combination of the three major experiments: TV (2,300 on first day), alpha scatter (43 hours surface analytical time), and surface sampler.
Apollo VIII	Dec. 21, 1968	Moon	First manned *Saturn V* flight: Frank Borman, James A. Lovell, Jr., and William A. Anders, demonstrated crew, space vehicle, and mission support facilities performance during 10 orbits around the Moon. Mission lasted 147 hours and returned to Earth Dec. 27, 1968.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
Mariner VI	Feb. 25, 1969	Mars	Planetary exploration: Mid-course correction successfully executed to achieve a Mars flyby within 3,330 km on July 31, 1969. Designed to perform investigations of atmospheric structures and compositions and to return TV photos of surface topography.
Mariner VII	Mar. 27, 1969	Mars	Planetary exploration: Spacecraft identical to *Mariner VI*. Mid-course correction successful for 3,518 km flyby on Aug. 5, 1969.
Apollo X	May 18, 1969	Moon	Manned lunar mission development flight to evaluate Lunar Module (LM) performance in the cislunar and lunar environment. Eugene A. Cernan, John W. Young, and Thomas P. Stafford. Major activities: descent of LM to within 50,000 feet of lunar surface and 19 color television transmissions. Pacific splashdown May 26, 1969. 192 hours duration.
Apollo XI	July 16, 1969	Moon	First manned lunar landing: conducted limited selenological inspection, photography survey, evaluation, and sampling of the lunar soil. Assessed the capability and limitations of astronauts and their equipment in the lunar environment. Astronauts: Neil A. Armstrong, Michael Collins, and Edwin E. Aldrin, Jr. Touchdown on lunar surface July 20. Pacific splashdown July 24, after a flight of 195 hours duration.
Apollo XII	Nov. 14, 1969	Moon	Second Manned lunar landing mission: demonstrated point landing capability, sampled more area, deployed ALSEP, investigated the *Surveyor III* spacecraft, and obtained photographs of candidate exploration sites. Astronauts: Charles Conrad, Jr., Richard F. Gordon, Jr., and Alan Bean. Touchdown on lunar surface was November 19. Total EVA time was 15 hours 30 minutes. Total flight time was 10 days, 4 hours 36 minutes. Splashdown Nov 24, 1969.
Apollo XIV	Jan. 31, 1971	Moon	Third manned lunar landing. Astronauts: Alan B. Shepard, Stuart A. Roosa, and Edgar D. Mitchell. Total flight time 216 hours. Splashdown occurred in Pacific Ocean on Feb. 9, 1971.
Mariner IX	May 30, 1971	Mars	Entered Mars orbit on Nov. 13, 1971. Spacecraft responsed to 38,000 commands and transmitted 6,900 pictures of the Martian surface. All scienfitic instruments operated successfully. Mission terminated on Oct. 27, 1972.
Apollo XV	July 26, 1971	Moon	Fourth manned lunar landing and first of *Apollo* "J" series missions which carried the Lunar Roving Vehicle. Astronauts: David R. Scott, Alfred M. Worden, and James B. Irwin. Total flight time: 295 hours. Total EVA time: 18 hours, 34 minutes. Worden conducted a 38-minute, in-flight EVA out of Earth orbit. Splashdown in Pacific about 300 nautical miles due north of Pearl Harbor on Aug. 7, 1971. Approximately 180 pounds of rock and soil samples returned.
Pioneer 10	Mar. 3, 1972	Jupiter	Investigation of the interplanetary medium, the asteroid belt, and the exploration of Jupiter and its environment. Closest approach to Jupiter 130,000 km on Dec. 3, 1973. Exited Solar System June 14, 1983; still active.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
Apollo XVI	Apr. 16, 1972	Moon	Fifth manned lunar landing; second of the *Apollo* "J" series with the Lunar Roving Vehicle. Astronauts: John W. Young, Thomas K. Mattingly II and Charles M. Duke. Total flight time was 266 hours. Total EVA time 20 hours 14 minutes. Mattingly's in-flight EVA was 1 hour 23 minutes. Splashdown in Pacific Ocean. April 27, 1972. Approximately 213 pounds of samples returned for scientific study.
Apollo XVII	Dec. 7, 1972	Moon	Sixth and last manned lunar landing; third of the *Apollo* "J" series which carried the Lunar Rover. Flight crew Eugene A. Cernan Ronald E. Evans, Harrison H. Schmitt spent 302 hours in flight. Cernan and Schmitt completed three EVAs lasting a total of 22 hours. The U.S.S. Ticonderoga recovered the crew and approximately 250 pounds of samples on Dec. 19, 1972.
Pioneer 11	Apr. 6, 1973	Jupiter/Saturn	Obtained scientific information beyond the orbit of Mars with the following emphasis; (a) investigation of the interplanetary medium; (b) investigation of the nature of the asteroid belt; (c) exploration of Jupiter and its environment. Closest approach to Jupiter 34,000 km on Apr. 19, 1974.
Mariner 10	Nov. 3, 1973	Venus/Mercury	Conducted exploratory investigations of the planet Mercury during three flybys by obtaining measurements of its environment, atmosphere, surface, and body characteristics, and conducted similar investigations of Venus. *Mariner 10* encountered Venus on Feb. 5, 1974 and Mercury on Mar. 29 and Sept. 21, 1974, and Mar. 16, 1975. Resolution of the photographs was 100 m, 7,000 times greater than that achieved by Earth-based telescopes.
Viking 1 Lander and Orbiter	Aug. 20, 1973	Mars	Scientific investigation of Mars. United States' first attempt to soft land a spacecraft on another planet. Successfully soft landed on July 20, 1976. First *in site* analysis of surface material on another planet.
Viking 2 Lander and *Orbiter*	Sept. 9, 1975	Mars	Scientific Investigation of Mars. United States' second attempt to soft land on Mars. Successfully soft landed on Sept. 3, 1976 and returned scientific data. Orbiter from both missions returned over 40,000 high resolution photographs showing surface details as small as 10 meters in diameter. The Orbiter also collected gravity field data, monitored atmospheric water levels, thermally mapped selected surface sites.
Voyager II *Voyager I*	Aug. 20, 1977 Sept. 5, 1977	Jupiter Saturn	*Voyager II* encountered Jupiter July 9, 1979 and Saturn Aug. 26, 1981. *Voyager I* encounted Jupiter Mar. 5, 1979, and Saturn Nov. 13, 1980. Both returned a wealth of information about these two giant planets and their satellites including documentation of active volcanism on Io, one of the Galilean satellites.
Pioneer 12 *Pioneer 13*	May 20, 1978 Aug. 8, 1978	Venus Venus	Orbiter launched in May studied interaction of the atmosphere and the solar wind and made radar and gravity maps of the planet. The multi-probe spacecraft launched in August returned information on Venus' wind and circulation patterns as well as atmospheric composition, temperature and pressure readings. *Pioneer 12* entered Venus orbit Dec. 4, 1978 and *Pioneer 13* encountered Venus Dec. 9, 1978.

(Excerpted from *Soviet Space Programs: 1976-80, Part 1*, December 1982, prepared by the Congressional Research Service.)

Payload Name	Designator	Launch Date	Mission	Remarks
Luna 1 (Mechta)	59 MU-1	Jan. 2, 1959	Moon strike	Missed Moon by 5,000-6,000 km Jan. 4, 1959, entered solar orbit.
Luna 2	591-X 1	Sept. 12, 1959	Moon strike	Struck Moon 435 km from visible center (1°W, 30°N).
Luna 3	59-Theta 1	Oct. 4, 1959;	Moon Pictures	Photos of farside of Moon returned by radio after flyby Oct. 10, 1959 at 6,200 km.
Venera 1	61-Gamma 1	Feb. 12, 1961	Venus	Passed Venus at 100,000 km May 19-21, 1961 but contact lost Feb. 27, 1961.
Mars 1	62-Beta Nu 3	Nov. 1, 1962	Mars	Passed Mars June 19, 1963 at 193,000 km, but communications failed March 21, 1963.
Luna 4	63-8B	April 2, 1963	Moon	Missed Moon by 8,500 km on April 6; barycentric orbit.
Zond 1	64-16D	April 2, 1964	Venus	Passed Venus at 100,000 km July 19, 1964; communications failed after May 14, 1964.
Zond 2	64-78C	Nov. 30, 1964	Mars	Passed Mars at 1,500 km Aug. 6, 1965; communications failed earlier.
Luna 5	65-36A	May 9, 1965	Moon	Struck Moon at 31°S, 8°W.
Luna 6	65-44A	June 8, 1965	Moon	Passed Moon at 160,000 km June 11, 1965; entered solar orbit.
Zond 3	65-56A	July 18, 1965	System Test	Passed Moon at 9,200 km, July 20, 1965; taking pictures, then flew as far as orbital path of Mars.
Luna 7	65-77A	Oct. 4, 1965	Moon	Struck Moon at 9°N, 40°W.
Venera 2	65-91A	Nov. 12, 1965	Venus	Passed Venus at 24,000 km, Feb. 27, 1966; communications failed.
Venera 3	65-92A	Nov. 16, 1965	Venus	Struck Venus March 1, 1966; communications failed earlier.
Luna 8	65-99A	Dec. 3, 1965	Moon	Struck Moon 9.1°N, 63.3°W.
Luna 9	66-6A	Jan. 31, 1966	Moon	Soft landed on Moon at 7.1N°, 64.3°W; returned pictures.
Luna 10	66-27A	March 31, 1966	Moon	Lunar orbit, April 3, 1966.
Luna 11	66-78A	Aug. 24, 1966	Moon	Lunar orbit, Aug. 29, 1966.
Luna 12	66-94A	Oct. 22, 1966	Moon	Lunar orbit, Oct. 25, 1966.
Luna 13	66-116A	Dec. 21, 1966	Moon	Soft landed on Moon at 18.9°N, 62°W; returned pictures.
Venera 4	67-58A	June 12, 1967	Venus	Probed atmosphere.
Zond 4	68-13A	March 2, 1968	Man precursor	Launched in direction away from Moon in test flight, probably returned to Earth.
Luna 14	68-27A	April 7, 1968	Moon	Lunar orbit April 10, 1968
Zond 5	68-76A	Sept. 14, 1968	Man precursor	Circumlunar, recovered, landed Indian Ocean.
Zond 6	68-101A	Nov. 10, 1968	Man precursor	Circumlunar, 2,420 km from Moon, Nov. 14. Landed U.S.S.R.
Venera 5	69-1A	Jan. 5, 1969	Venus	Entered Venus atmosphere May 16, 1969.

Payload Name	Designator	Launch Date	Mission	Remarks
Venera 6	69-2A	Jan. 10, 1969	Venus	Entered Venus atmosphere May 17, 1969.
Luna 15	69-58A	July 13, 1969	Moon	Lunar orbit, then crashed in soft landing attempt.
Zond 7	69-67A	Aug. 7, 1969	Man precursor	Circumlunar, 2,200 km from Moon, Aug. 11. Landed U.S.S.R.
Venera 7	70-60A	Aug. 17, 1970	Venus	Soft landed on Venus, signal from surface.
Luna 16	70-72A	Sept. 12, 1970	Moon	Automated return of soil sample to Earth.
Sample Returner	70-72E	Sept. 21, 1970 (from Moon)	Carry lunar soil	Recovered in U.S.S.R.
Zond 8	70-88A	Oct. 20, 1970	Man precursor	Circumlunar, passed 1,120 km of Moon Oct. 24, landed in Indian Ocean.
Luna 17	70-95A	Nov. 10, 1970	Moon	Landed Lunokhod roving surface vehicle 756 kg, after orbiting Moon.
Kosmos 419	71-42A	May 10, 1971	Mars	Failed to separate.
Mars 2-Orbiter	71-45A	May 19, 1971	Mars	Orbited Mars Nov. 27, 1971. *Mars 2* Orbiter and Lander launched from single D class vehicle (Proton), 4,650 kg thrust.
Mars-Lander	71-45E	May 19, 1971	Mars	Landed 47°E
Mars 3-Orbiter	71-49A	May 28, 1971	Mars	Orbited Mars Dec. 2, 1971. Mars 3 Orbiter and Lander launched from single D class vehicle (Proton), 4,650 kg thrust.
Mars 3-Lander	71-49F	May 28, 1971	Mars	Landed 45°S, 158°W.
Luna 18	71-73A	Sept. 2, 1971	Moon	Orbited Moon, but destroyed in soft landing attempt.
Luna 19	71-82A	Sept. 28, 1971	Moon	Orbiter only. Returned pictured by radio.
Luna 20	72-7A	Feb. 14, 1972	Moon	Orbited Moon, then soft landed.
Sample Returner	72-7F	Feb. 22, 1972 (from Moon)	Moon	Recovered in U.S.S.R.
Venera 8	72-21A	Mar. 27, 1972	Venus	Soft landed on Venus; sent data from surface.
Luna 21	73-1A	Jan. 8, 1973	Moon	Orbited Moon, landed Lunokhod 2 roving laboratory (840 kg) at 26.5°N., 30.6°E.
Mars 4	73-47A	July 21, 1973	Mars	Passed Mars at 2,200 km Feb. 10, 1974, but failed to enter Mars' orbit as planned.
Mars 5	73-49A	July 25, 1973	Mars	Orbited Mars Feb. 2, 1974 to gather Mars data and to serve as relay station.
Mars 6-orbiter	73-52A	Aug. 5, 1973	Mars	Mars 6 Orbiter and Lander launched from single D class vehicle (Proton) 4,650 kg thrust.
Mars 6-Lander	73-52E	Aug. 5, 1973	Mars	Soft landed at 24°S, 25°W; returned atmospheric data during descent.
Mars 7-Orbiter	73-53A	Aug. 9, 1973	Mars	Mars 7 Orbiter and Lander launched from single D class vehicle (Proton), 4,650 kg thrust.
Mars 7-Lander	73-53E	Aug 9, 1973	Mars	Missed Mars by 1,300 km (aimed at 50°S, 28°W).
Luna 22	74-37A	May 29, 1974	Moon	Placed in lunar orbit June 2, 1974.

Payload Name	Designator	Launch Date	Mission	Remarks
Luna 23	74-84A	Oct. 28, 1974	Moon	Orbited Moon, landed at 13.5°N, 56.5°E to drill for soil sample.
Sample Returner	74-84E	None	Moon	Failed to launch because drill damaged.
Venera 9-Orbiter	75-50A	June 8, 1975	Venus	Orbited Venus Oct. 22, 1975. Orbiter and Lander launched from single D-Class vehicle (Proton), 4,650 kg thrust.
Venera 9-Lander	75-50D	June, 1975	Venus	Soft landed, returned picture.
Venera 10-Orbiter	75-54A	June 14, 1975	Venus	Orbited Venus Oct. 25, 1975. Orbiter and Lander launched from single D-class vehicle (Proton), 4,659 kg thrust.
Venera 10-Lander	75-54D	June 14, 1975	Venus	Soft landed, returned picture.
Luna 24	76-81A	Aug. 9, 1976	Moon	Orbited Moon, landed at 21.7°N 62.2°E to drill sample.
Sample Returner	76-81E	Aug. 19, 1976 (from Moon)	Moon	Recovered in U.S.S.R.
Venera 11-Orbiter	78-84A	Sept. 9, 1978	Venus	Passed Venus at 35,000 km Dec. 25, 1978; served as relay station. Orbiter and Lander launched from single D-class vehicle (Proton) 4,650 kg thrust.
Venera 11-Lander	78-84E	Sept. 9, 1978	Venus	Soft-landed on Venus.
Venera 12-Orbiter	78-86A	Sept. 14, 1978	Venus	Passed Venus at 35,000 km Dec. 21, 1978, served as relay station. Orbiter and Lander launched from single D-class vehicle (Proton), 4,650 kg thrust.
Venera 12-Lander	78-86E	Sept. 14, 1978	Venus	Soft-landed on Venus.

SUPPLEMENT TO

U.S.S.R. Lunar and Planetary Missions through 1980

Payload Name	Designator	Launch Date	Mission	Remarks
Venera 13-Orbiter	1981-106A	Oct. 30, 1981	Venus	Both Orbiter and Lander launched from single D-class vehicle (Proton), 4,650 kg thrust.
Venera 13-Lander	None	Oct. 30, 1981	Venus	Soft-landed on Venus Mar. 3, 1982; Returned Color Picture.
Venera 14-Orbiter	1981-110A	Nov. 4, 1981	Venus	Both Orbiter and Lander launched from single D-class vehicle (Proton), 4,650 kg thrust.
Venera 14-Lander	None	Nov. 4, 1981	Venus	Soft-landed on Venus Mar. 5, 1982; returned color picture.

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After closest approach to Neptune and its moon, Triton, on August 24, 1989, Voyager 2 *will head out of the solar system.*